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JOUKO SAARELA

Hydraulic approximation of infiltration  
characteristics of surface structures  
on closed landfills

MONOGRAPHS

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Boreal Environment Research

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MONOGRAPHS OF THE BOREAL ENVIRONMENT RESEARCH

**3**

Jouko Saarela

**Hydraulic approximation of infiltration characteristics of surface structures on closed landfills**

Yhteenveto: Peiterakenteiden imeytymisominaisuuksien hydraulinen arviointi suljetuilla kaatopaikoilla

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# Contents

<b>1 Introduction</b>	<b>8</b>
1.1 Background of the study	8
1.1.1 General	8
1.1.2 Construction of old landfills	8
1.1.3 State of closed landfills in Finland	8
1.2 Aims of the study	9
1.3 Limitations of the study	10
1.4 Structure of the study	10
<b>2 Surface structures of landfills and factors affecting them</b>	<b>10</b>
2.1 Function and attributes of surface structures	10
2.2 Special features of landfills	12
2.2.1 General	12
2.2.2 Assumed materials, actual condition and hydrological conditions of landfill	12
2.2.3 Stability of landfills	13
2.2.4 Compression and settlement of landfills	16
2.2.5 Compaction of landfill	17
2.2.6 Hydraulic conductivity of wastes	18
2.2.7 Landfill gas	19
2.3 Materials used in surface structures of landfills	21
2.3.1 The use of soil materials	21
2.3.2 The use of industrial waste and other similar materials	22
2.3.3 Geomembranes, geotextiles and bentonite	23
2.4 Parts of surface structures of landfills	24
2.4.1 Background	24
2.4.2 Landfill gas control layer	24
2.4.3 Filter layers	24
2.4.4 Foundation (Buffer) layer	25
2.4.5 Hydraulic barrier	26
2.4.6 Drainage layer	26
2.4.7 Biotic barrier	26
2.4.8 Vegetation layer and landscaping	27
2.5 Additional factors affecting design of surface structures	29
2.5.1 Enduse of landfill sites	29
2.5.2 Surface water management	30
2.5.3 Frost action	30
2.5.4 Snow removal	31
2.6 Choice of surface structures for covering landfills in Finland	31
2.6.1 Background	31
2.6.2 Types of surface structures	32
2.6.3 The choice of structure type and requirements for the hydraulic barrier	33
2.6.4 Factors and remedial measures to be taken into consideration in the use of soil materials in the hydraulic barrier	33
2.6.5 Construction costs, construction and quality control	34

### 3 Earlier models and development of the Landfill

<b>Cover Approximation Model (LCAM)</b>	<b>34</b>
3.1 Background	34
3.2 Earlier models	34
3.2.1 Water Balance Method (WBM)	34
3.2.2 Improved water balance methods	36
3.2.3 LANCEL model	38
3.2.4 Numerical solution of flow through landfills	40
3.2.5 Use of a groundwater model in the landfill water balance	41
3.2.6 Stochastic approach to precipitation	41
3.3 Structure of LCAM	42
3.3.1 Two presuppositions of LCAM	42
3.3.2 Main components of LCAM	42
3.3.3 Equations of LCAM	43
3.3.4 The variables of LCAM	47
3.3.5 The comparison of LCAM to other models	48
3.4 Effects of primary assumptions on accuracy of numerical analysis in LCAM	49
3.4.1 Presuppositions	49
3.4.2 The quasi 3-D water balance model of a landfill	49
3.4.3 Numerical analysis of infiltration	49
3.4.4 Two-dimensional groundwater flow	49
3.4.5 Parameters required for the quasi 3-D model	50
3.4.6 Water movement in soil	51
3.5 Comparison of results given by the quasi 3-D model and LCAM	53
3.5.1 Numerical analysis with the quasi 3-D model and LCAM	53
3.5.2 Uncertainty sources of the quasi 3-D model	56

### 4 Testing of LCAM 60

4.1 Background	60
4.2 Field investigations of the test landfills	60
4.3 Results of the field investigations of the test landfills	61
4.4 The quantities of the leachate waters measured in the test landfills and calculated by LCAM	61
4.4.1 Background	61
4.4.2 The measurements of leachate waters in the landfills and their error sources	66
4.4.3 Circumstances of measurements of leachate waters	66
4.4.4 Input data in the testing of LCAM	66
4.4.5 Results from the testing of LCAM	72
4.4.6 Relation between the infiltration and the surface runoff	73
4.4.7 Reliability of LCAM	73

### 5 Simulation of different factors in the approximation of the surface structures of the landfills with LCAM 73

5.1 Background	73
5.2 Input data and the structures analysed	73
5.3 Effects of different factors	74
5.3.1 Effects of the surface soil layer	74
5.3.2 Effects of the vegetation	74
5.3.3 Effects of the snow removal	74
5.3.4 Effects of the drainage layer	76
5.4 Costs comparison of different factors	76

5.5 Estimation of the surface structures chosen for covering Finnish landfills using the results of the simulation by LCAM .....	76
5.5.1 Background .....	76
5.5.2 Relations between the hydraulic barrier, vegetation, drainage layer and snow removal .....	77
5.6 Practical examples for the use of the results of simulation by LCAM in the approximation of infiltration into the wastefill .....	82
<b>6 Discussion .....</b>	<b>84</b>
6.1 Aspects to be considered in the closing of landfills .....	84
6.2 Phases of the closing of landfills .....	84
6.3 Reliability of results and error estimation .....	87
<b>7 Conclusions and recommendations .....</b>	<b>89</b>
<b>Acknowledgements .....</b>	<b>90</b>
<b>Yhteenveto .....</b>	<b>91</b>
<b>List of symbols .....</b>	<b>92</b>
<b>Abbreviations .....</b>	<b>93</b>
<b>References .....</b>	<b>93</b>
<b>Appendices .....</b>	<b>103</b>
<b>Appendix 1, Pilot investigations of surface parts of closed landfills for testing of LCAM .....</b>	<b>104</b>
<b>Appendix 2, Summary of the national survey of closed landfills .....</b>	<b>122</b>
<b>Appendix 3, The variables of LCAM .....</b>	<b>135</b>





# Hydraulic approximation of infiltration characteristics of surface structures on closed landfills

Jouko Saarela

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This study deals with hydraulic approximation of infiltration characteristics of surface structures on closed landfills. There are several water balance models available for landfill water balance in different countries but they are not directly usable in Finnish conditions or they are too complicated for practical purposes. With the model developed and tested in this study the different factors in surface structure of landfills can be approximated in Finnish conditions. However, in future it is worthwhile to monitor the results obtained by the developed Landfill Cover Approximation Model (LCAM) and to continue the testing in different situations because in this work it could be tested only in a limited scale. The testing and the simulation proved that the model does not need the pF-curve of waste as an input parameter because the hydraulic conductivity of landfill waste is, according to earlier studies, so great that the hydraulic conductivity of the hydraulic barrier is the critical factor in simulations. The main components which have the greatest effect on the quantity of infiltration into the wastefill are the hydraulic conductivity of the hydraulic barrier, vegetation, snow removal and the drainage layer. In approximations, design diagrams presented in this study can be used and in the exact analysis LCAM can be used. For practical purposes different aspects to be considered in the closing of landfills are also presented. On the grounds of the study, this makes the controlled reduction of leachate waters of closed landfills possible. Designers of waste management systems can analyse all the aspects of landfill closure using the modelling results and principles of greenbuilding presented in this study. Closure of landfills does not need to remain at the minimum level of environmental protection. By choosing an enduse suitable for the site and size of landfills, they can be taken into active use and as part of communal landuse.

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**Keywords:** Landfills, sanitary landfills, surface structures, leachate, infiltration, hydraulic conductivity, water balance of landfills.

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## 1 Introduction

### 1.1 Background of the study

#### 1.1.1 General

According to the national landfill register there were 644 open landfills in Finland in 1994 of which 446 were used primarily for municipal solid waste disposal. In the register 1 162 landfills were classified as closed. Due to inadequate registration, the total number of the closed landfills is probably higher than reported (Table 1, in App. 2).

The number of open landfills in Finland is high compared, for example, to Sweden where in 1993 there were about 300 landfills (Kettunen 1995). Finland's Ministry of the Environment has set a target to cut the number of landfills to 200–250 by the year 2000. The aim is to encourage communities to cooperate in waste management and to set up common landfills. Therefore, for example, the size of landfills will grow in the future.

It is seen that almost 500 landfills will be closed in Finland by the end of this century. The great number of landfills to be closed and the pressure in organizing their aftercare helped to initiate and affect the content of this study. According to the current trend they will be covered with different kinds of surface structures. The most important task of surface structures is to minimize the quantity of infiltration of precipitation into landfills. Landfills without a proper surface cover can cause environmental hazards with potential aesthetic and hygienic disadvantages, the most serious being the contamination of groundwaters. For this reason, surface structures must be built with care. On the other hand, there is no reason for extra security in the surface structures because construction work is expensive.

In the national survey of closed landfills (see App. 2) it was seen that landfills did not fulfill environmental requirements concerning design, construction, minimization of leachate, landscaping and afteruse. The observed deficiencies were due to the fact that the research of waste management is a new science and the designers of waste management have not had enough research results on surface structure design and research available. Many failures of sludge ponds in landfills that occurred before dam safety legislation were also because, in general, the structures have not been designed and constructed properly. Landfills can also

contain many kinds of toxic materials, which can have effects on the structures, for example, on the vegetation layer, and they must also be taken into consideration in field investigations and in construction work of surface structures.

A multidisciplinary approach is needed in the research of surface structures of landfills. A knowledge in several sciences is required, for example, in environmental geotechnology, geotechnical engineering, waste management, water resource management, hydrology, geology and landscaping.

#### 1.1.2 Construction of old landfills

The old landfills were constructed without plans for the location and foundation of the landfills. The newer landfills generally have construction plans that fulfill the requirements at the time of construction. They are, in general, founded on natural soil layers. According to Kolehmainen (1980), 35 % of the landfills are founded on peat lands. Suomela (1984) has obtained the same results in his research. According to Saarelainen *et al.* (1985), probably the greatest part of Finnish landfills are situated, at least partly, on peat lands or their near surroundings. In 1970's and 1980's inner and outer ditches, and leachate basins were constructed for landfills. Bottom liners and underdrains were not, in general, constructed in landfills. Surface structures were poorly designed and constructed.

According to Tolppanen (1994) 154 functioning or closed landfills are situated on important groundwater areas or their near surroundings. It is estimated that 117 of them are landfills for municipal wastes and it is known or suspected that 37 landfills contain hazardous wastes. It is estimated that 71 landfills affect the quality of local groundwaters. There are 14 landfills for municipal wastes estimated to be in the areas of groundwater pumping stations. It is estimated that 10 landfills containing hazardous waste affect the quality of groundwaters. In the areas of pumping stations, probably 17 landfills contain hazardous wastes that may affect the quality of groundwaters.

#### 1.1.3 State of closed landfills in Finland

One aim of the survey of closed landfills (Saarela 1994a, App. 2) was to investigate how closed landfills were covered and to make recommenda-

tions for measures to improve the practice of landfill coverage for Finnish conditions.

The survey performed in 1990 concerned 157 randomly chosen landfills that contained household and industrial wastes.

The name of landfill, foundation and closing year, locality, quality of waste, height, area, failures, material and construction of surface structures, quality control of leachate waters, environmental consequences of leachate waters, landscaping and afteruse were recorded.

About one half of the landfills was for household and industrial wastes, the other one only for household wastes, and only a small part of landfills was for industrial wastes only.

The age of the majority of landfills (about 40 %) was 15–20 years. The height of the majority of landfills (about 55 %) was less than 5 m. The area of the majority of landfills (about 40 %) was less than 0.5 hectares. The majority of landfills was covered by excess soil (about 65 %). Almost all landfills were closed without any proper closing plans.

Several landfills have had failures due to stability problems. The majority of landfills (about 80 %) did not have a proper enduse. The landscaping of landfills was also, in general, very poor and the majority of landfills (about 70 %) was not landscaped.

More than a half of the landfills (about 60 %) had no quality control of leachate waters and when quality control of leachate water was done, it was very uneven due to the great differences in size, location and type of landfills. The quality control could vary from an one-off sample to several annually taken samples.

Part of the landfills (about 20 %) had caused contamination of groundwaters or negative changes in the ground- or surface waters.

In the survey, it was clearly seen that the closure of landfills in Finland did not fulfil the requirements of modern landfill technology and the environmental requirements concerning planning, construction, minimization of leachate waters, landscaping and enduse.

Recommendations of the survey were that in Finland a research project concerning the closure of landfills should be started and it should develop and test, among other things, a Landfill Cover Approximation Model for Finnish conditions. A more complete summary of the results of the survey is presented in App. 2.

## 1.2 Aims of the study

This study deals with hydraulic approximation of infiltration characteristics of surface structures on closed landfills. There are several water balance models available for landfills in different countries but they are not directly usable in Finnish conditions or they are too complicated for practical purposes.

The main aim of the study was to develop and to test such a Landfill Cover Approximation Model which would make it possible to approximate different factors of the surface structures in reducing and controlling the quantity of the infiltration of the annual precipitation into the wastefill in Finnish conditions.

Another central aim was to simulate the effects of the thickness and the hydraulic conductivity of the hydraulic barrier, the thickness and the hydraulic conductivity of the surface layer, vegetation, snow removal and drainage layer to reduce the quantity of the infiltration into the wastes.

The next aim was to find out general points to be considered in the closing of landfills, which make the controlled reduction of the leachate waters of closed landfills possible. The aim was also to develop with the help of the model a design code of practice for surface structures of landfills.

After reaching these goals, the aim was to choose a selection of surface structure types for Finnish conditions using the results of the survey of closed landfills and earlier research results concerning surface structure design in different countries. The attributes of these structures could be tested by the model.

The aim of the literature research was to obtain information on surveying of surface structures design and waste characteristics e.g. stability, compression, settlement, compaction, hydraulic conductivity of wastes, landfill gas, vegetation and landscaping.

The aim was also to perform some pilot investigations on existing surface structures of closed landfills for the proper model testing.

When determining input parameters for the Landfill Cover Approximation Model and the investigation methods to obtain them, it was also intended that the model would not need the pF-curve of waste as an input parameter.

### 1.3 Limitations of the study

- In testing the model, the measurements of the leachate waters could not be done under controlled circumstances and impreciseness of the measurements has caused uncertainty in the results. A more controlled way of testing would have been to measure infiltration, surface runoff and surface layer runoff separately, but under the test conditions of this research this was impossible.
- Different research and testing methods were tested only in a limited scale.
- The model concerns natural soils or materials behaving like them.

### 1.4 Structure of the study

The structure of the study can be divided to the following parts (Fig. 1).

- The survey of closed landfills to investigate how closed landfills were covered and to make recommendations for measures to improve the practice of landfill coverage in Finnish conditions.
- The literature research concerning surface structures and factors affecting them e.g. waste characteristics, stability, compression, settlement, hydraulic conductivity and compaction of waste, landfill gas, vegetation and landscaping.
- The choice of surface structure types for Finnish conditions and preliminary pilot investigations concerning surface structures of landfills.
- The literature research on the modelling of water balance of landfills.
- The development of the Landfill Cover Approximation Model for Finnish conditions and its comparison to other models developed in different countries.

- Tests and simulations of the model and tests of the chosen surface structure types for Finnish landfills with the model.
- Design diagrams from the model for surface structures of landfills.
- Combined results of the study with the aspects to be considered in the closing of landfills.
- Conclusions, recommendations, and further research.

## 2 Surface structures of landfills and factors affecting them

### 2.1 Function and attributes of surface structures

The risk to human health and the environment caused by landfilling has become an important contemporary issue. It is recognised that any wastes containing contaminants may in turn generate a corresponding quantity of contaminated leachate. For many sites precipitation is the predominant source of water intrusion. It is therefore essential to design and construct an effective long term barrier for the surface.

A cover at a landfill site is an earthwork construction designed to exclude precipitation from contact with disposed wastes, to act as a barrier against human or animal contact with the wastes and to prevent release of vapours to the environment. Covers are preventive measures used in most landfills. They are seldom used alone but are part of an integrated concept of waste containment.

**Table 1.** Cover functions and attributes (McAneny and Hatheway 1985).

Functions	Necessary Attributes
Prevention or Minimization of Percolation	Promotion of Site Reclamation
Promotion of Aesthetics	Water Erosion Resistance
Suppression of Vectors	Wind Erosion Resistance
Containment of Gases	Stability against Slope Failures
Suppression of Fire Danger	Stability against Slumping and Cracking
Prevention of Blowing Litter or Dust	Resistance to Cold Weather Distress
	Resistance to Disruption by Animals or Plants

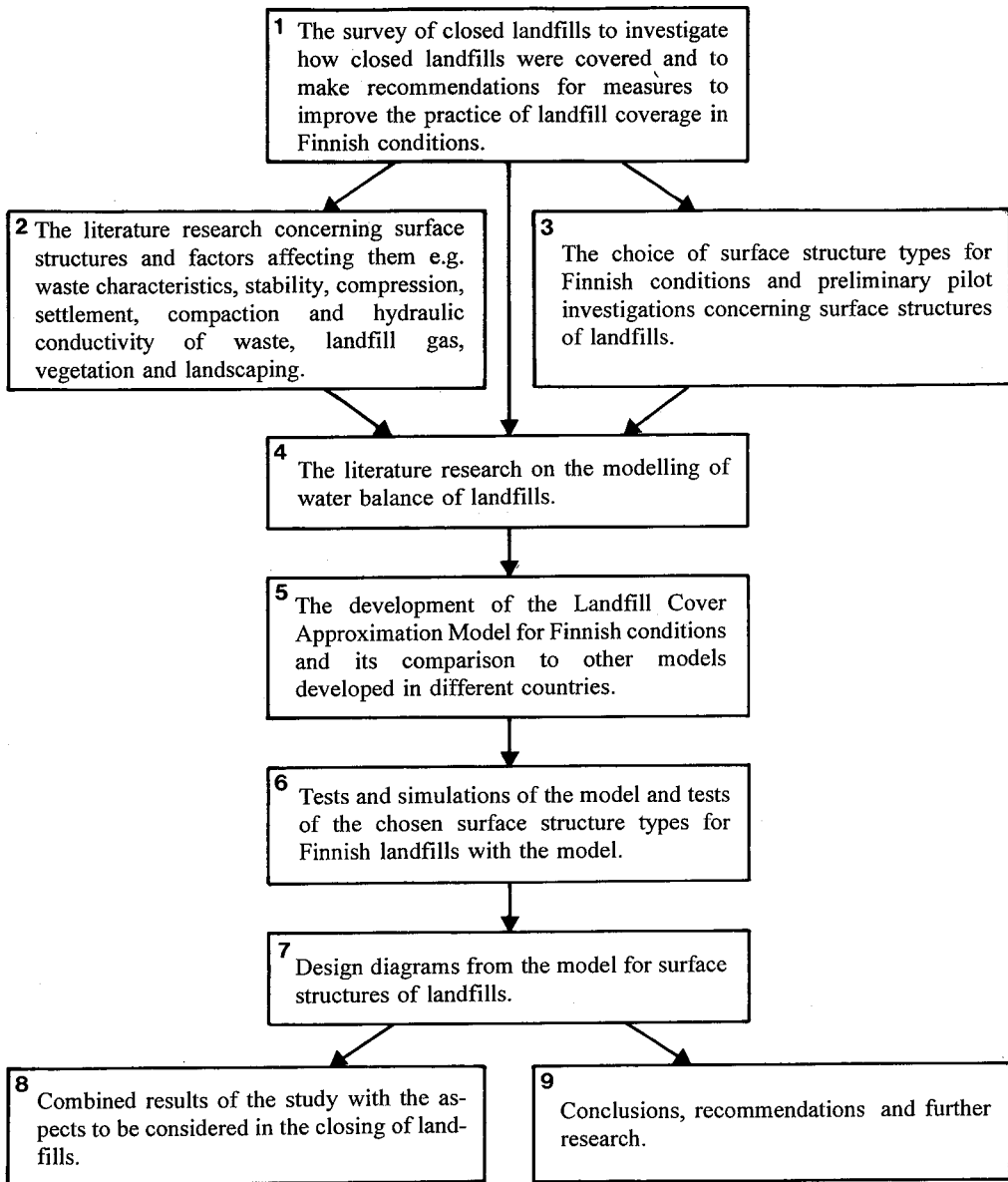


Fig. 1. Schematic diagram of the study. Numbers refer to the study order.

A cover may perform a number of functions, as listed in Table 1. Fig. 2 shows an illustration of the major environmental aspects related to landfilling. Functions along with their necessary attributes are listed. Attributes pertain mainly to the cover's own durability and permanence. The purpose of good design is to provide these attributes while assuring the performance of the desired functions.

While all of the functions are important, preventing percolation is predominant, because contamination of ground- and surface water supplies is the most serious threat of landfills. Fig. 3 shows an example of a cover components system.

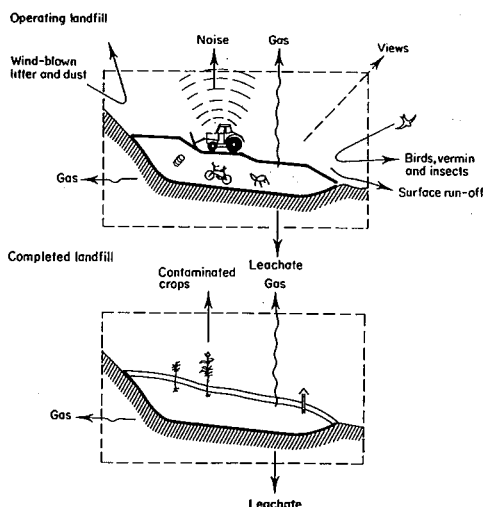


Fig. 2. Illustration of the major environmental aspects related to landfilling (Christensen 1989).

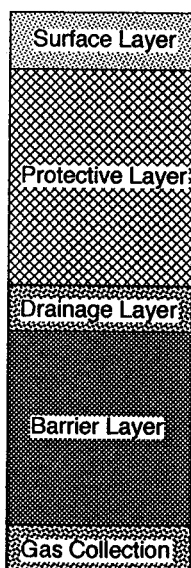


Fig. 3. An example of the components of a cover system (Daniel 1993).

## 2.2 Special features of landfills

### 2.2.1 General

Landfills have many special features and they differ considerably from, for example, a mine waste or a building waste area because in these cases settlement can usually be controlled with com-

paction by earthmoving machinery during the period when the tip is being built up. A landfill, for example, suffers considerable settlement by the decomposition of the organic contents over a long period of time. The other problem is gas generation in relation to the engineering of landfill reclamation for buildings and vegetation. These all, and other features, must be taken into consideration in surface structures. Therefore, information such as the assumed materials of the landfill, its actual condition, hydrological conditions, stability, waste characteristics, settlement, hydraulic conductivity, and gas formation must be obtained. If some of the above factors are assumed to cause difficulties in the planning and construction of surface structures the matter must be resolved. For example, when the stability of a landfill is not adequate and failures are expected to occur or if the landfill is not compacted enough, then the landfill will probably have great deformations.

Chapters 2.2.2–2.2.7 deal with the results of different reports concerning waste characteristics, stability, compression, settlement, compaction, hydraulic conductivity of wastes and gas formation in landfills, which all must be taken into consideration in the design of surface structures for landfills. The results of different investigations can vary greatly due to differences in the quality of waste, investigation conditions and because landfill research is a new science and does not always have standardized investigation methods.

### 2.2.2 Assumed materials, actual condition and hydrological conditions of landfills

In the closing of a landfill, the assumed waste materials, actual condition and hydrological conditions of a landfill must be investigated first, for example:

- quality of wastes and their location in the landfill
- hydrological and geological conditions of the landfill
- construction stages of the landfill, layer zones and hydraulically conductive zones
- filling methods of wastes at the landfill, density, hydraulic conductivity and homogeneity of wastes
- weak zones clarified with planning documents, by investigations, or by earlier documented

- failures or settlements of the landfill or its foundations
- drainage system and other water conducting structures and inspection wells.

### 2.2.3 Stability of landfills

If the stability of a landfill is not sufficiently good, other measures concerning the design of the surface structures cannot be carried out if the stability has not been checked and secured, and if needed also improved. Then one must ensure, among other things, that the landfill can stand the extra weight caused by surface structures without failure. Stability of the landfill depends on the strength and the deformation properties of the ground and the waste materials and the water pressure in the ground and landfill. According to Jessberg and Klos (1992), when considering landfill stability and deformation problems, it is convenient to identify two basic aspects, external and internal stability (Fig. 4). External stability refers to the stress and deformation behaviour of the waste influencing potential failure zones for all slopes (temporary and final), and in the surrounding of the waste body both during and after the operational phase. It also refers to the sliding resistance of lining systems. Depending on the type and composition of the lining system, interfaces between different lining elements with low shear resistance may occur, leading to a shear failure along these zones. Internal stability relates to placement criteria of wastes which are not placed within external stability zones.

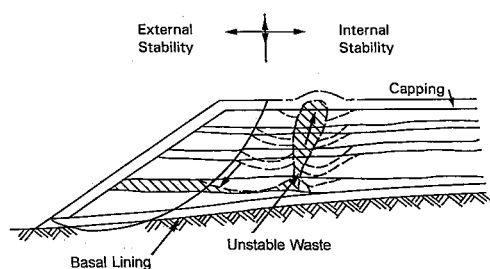


Fig. 4. Inner and outer stability of a landfill (Jessberger and Klos 1992).

According to Cancelli (1989), heterogeneity, nature and size of different components of urban wastes do not allow easy and reliable determina-

tion of drained shear strength parameters to be introduced into stability analyses. The little data collected from literature is plotted and compared in Fig. 5; on this basis, the following values of the effective shear strength parameters may be assumed for a routine design; the angle of friction =  $25^{\circ}$ – $26^{\circ}$ ; and cohesion limited to a maximum of 30 kPa.

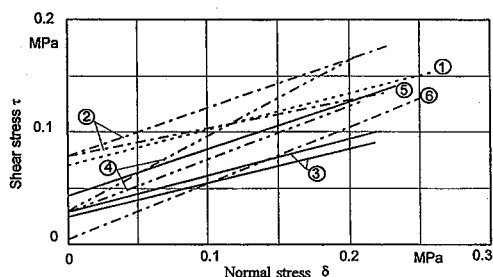


Fig. 5. Summary of effective stress envelopes for landfill wastes (Cancelli 1989). Sources of data: (1) from laboratory tests (Fang *et al.* 1977); (2) extreme values from laboratory tests (Fang 1983); (3) suggested values for landfill design (Oweis *et al.* 1985); (4) extreme values suggested by STS (1985); (5) suggested values (Chen 1986); (6) back-computed values (Tonteri and Lindroos 1987); (2), (3), (4) after Oweis and Khera (1986).

According to Petäjä (1985), from back-computed calculations of failures of landfills, the angle of friction of wastes can be supposed to be  $34^{\circ}$ – $38^{\circ}$  and the cohesion 0. These values are equivalent to dense sand and loose gravel.

Dulpancic *et al.* (1987) have used a value of  $31^{\circ}$  for the angle of friction, and cohesion of 0 in the design of surface structures of a landfill for hazardous wastes.

According to Seed (1994), the ranges of the angle of friction for "common municipal waste", currently used in recent U.S. practice, appear to be from  $20^{\circ}$  to  $40^{\circ}$ .

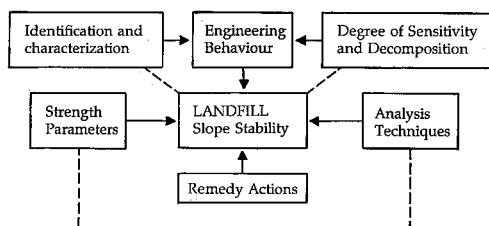
According to Saarela (1979), the most problematic waste materials in a landfill are sludges and clays. These materials can be placed in ponds, which are covered with waste. If they are on slopes, they can cause weakness zones. Their angle of friction is small when they are placed in a landfill, they behave almost like liquids. The bulk unit weight of soft clay and sludge is

11–14 kN m<sup>-3</sup>. When they are covered with another material mass, their consolidation starts. The process of consolidation depends on drainage conditions among other things. The best materials in landfills are non-cohesive soil and ash. Bottom slag can be used instead of gravel. Its compacted unit weight is 13–16 kN m<sup>-3</sup> and the angle of friction 35°–40°.

According to Saarela (1979), the dry unit weight of compacted landfill waste material was 3–5 kN m<sup>-3</sup>. According to the three-axial compression test on waste materials the angle of friction was 20° and cohesion 70 kN m<sup>-2</sup>. However, in a landfill the properties of wastes can change. In the Iso-Huopalahti landfill in Helsinki, it was found by Saarela (1979) that at the depth of 20 m the bulk unit weight of waste was 17–19 kN m<sup>-3</sup> and near the surface 12 kN m<sup>-3</sup>. From the resistance of drilling it was estimated that the strength of waste at the depth of 20 m is equal to that of soil, which has an angle of friction 42°–45° and near the surface 32°–36°.

In Finland failures in landfills have occurred. In autumn 1985 there was a failure in the Mankkaa landfill. It was caused by placing loose soil masses on the landfill (Tonteri and Lindroos 1987, Viatak Oy 1990). In the Iso-Huopalahti and Vuosaari landfills there have been failures due to the wrongful placing of loose soil masses in the 1980s. Before dam safety legislation in Finland there have been several failures of sludge ponds in landfills (Saarela 1990a). Reasons for the failures have been inadequate design, construction and overfilling of dams.

Fang (1995a) has dealt with the landfill slope stability analysis. An overall system of stability of slope of landfill is presented in Fig. 6.



**Fig. 6.** Stability of the slope of a landfill-genetic diagnosis approach (Fang 1995a).

According to him, slope stability analysis in landfills relates to two cases i.e. fill and cut conditions.

Case 1. During the waste disposal process, the slope at the landfill site is in the fill stage. One needs to know how high the landfill can be made without slope failure. In this situation the critical height ( $H_{cr}$ ) of the slope is the most important factor. (Fig. 7a).

Case 2. When old or abandoned landfill sites are to be developed for other purposes, such as commercial parking lots, recreation parks, or as part of highway routes etc., excavation into the landfill is sometimes necessary for construction purposes. In such a case, it is the slope angle ( $\beta$ ) that is important (Fig. 7a).

In general, landfill slope failure is similar to slope failure in earth or rock slopes apart from the exceptions caused by highly nonhomogeneous materials and a nonuniform decomposition process, and the types of failure also include falls, slips and slides. Falls and topples are due to lack of cohesion between loose waste pieces.

Slope failure potential is directly related to the compaction control during the waste disposal process. The better the control of the compaction, the less is the risk of slope failures. Fig. 8 illustrates some typical landfill slope failures:

- differential decomposition due to weathering (Fig. 8a).
- lack of cohesion between two or more waste materials (Fig. 8b)
- hydrostatic or environmental forces acting on decomposed or loosened waste pieces (Fig. 8c)
- different decomposition and differential settlement causing slope cracks and falls (Fig. 8d)
- chemical corrosion of some supported waste material erodes the support and results in failure (Fig. 8e).

Characteristics of waste which lead to slope stability problems include:

- highly nonhomogenous materials
- nonuniform decomposition processes
- nonuniform rate of settlement (high differential settlement).
- the waste itself is an unstable material and cannot take both vertical and horizontal loads.
- pore water pressures are varied.

Based on the nature of waste and the characteristics of landfill sites three basic problems must be evaluated:

- complex material composition



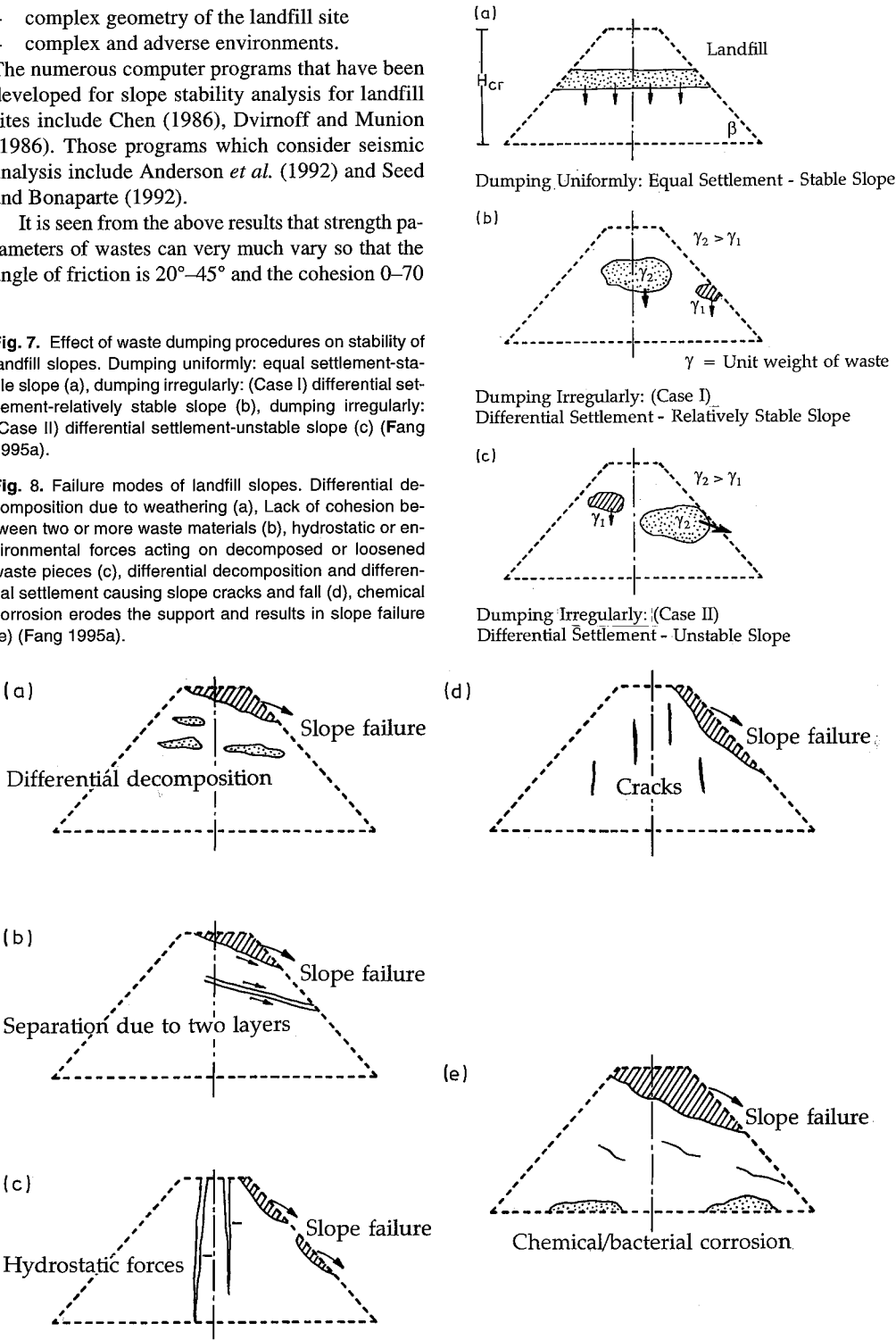
– complex geometry of the landfill site  
– complex and adverse environments.

The numerous computer programs that have been developed for slope stability analysis for landfill sites include Chen (1986), Dvornoff and Munion (1986). Those programs which consider seismic analysis include Anderson *et al.* (1992) and Seed and Bonaparte (1992).

It is seen from the above results that strength parameters of wastes can very much vary so that the angle of friction is 20°–45° and the cohesion 0–70

**Fig. 7.** Effect of waste dumping procedures on stability of landfill slopes. Dumping uniformly: equal settlement-stable slope (a), dumping irregularly: (Case I) differential settlement-relatively stable slope (b), dumping irregularly: (Case II) differential settlement-unstable slope (c) (Fang 1995a).

**Fig. 8.** Failure modes of landfill slopes. Differential decomposition due to weathering (a), Lack of cohesion between two or more waste materials (b), hydrostatic or environmental forces acting on decomposed or loosened waste pieces (c), differential decomposition and differential settlement causing slope cracks and fall (d), chemical corrosion erodes the support and results in slope failure (e) (Fang 1995a).



kN m<sup>-2</sup> depending on the composition of different components, such as their compactability, daily cover, moisture absorption, age and state of decomposition. Compared to the values presented by Petäjä (1985), obtained by back-calculated failures of landfills, it can be said that they represented the mean values for the angle of internal friction (34°–38°). Cohesion was zero. However, according to Zadroga (1994), the angle of friction decreased with time. According to different sources collected by Zadroga, the angle of internal friction might be assumed to be 40° for new waste, for five year old waste it was 30°, for ten year old waste it was about 25°, for 20 year old waste it was about 23° and for 30 year old waste it was about 20°. The angle of internal friction of old and completely decomposed waste might be 18°.

In summary, the investigation into the stability of a landfill is very important because, for example, all the major landfills (Iso-Huopalahti, Mankkaa, Vuosaari) in the Helsinki area have had failures (Saarela 1994a). They may have occurred because the stability has not been taken sufficiently into consideration in the placing of waste materials. The stability of the landfill can be improved by making slopes more gentle by a different arrangement of the waste and making the waste body lower. Saarela (1990b) has dealt with the improvement in the stability of slopes and other methods of rehabilitation of tailing areas of mines. The same principles can be also used for the improvement of slopes of landfills.

Also, landfill mining must be taken into consideration for the improvement of slopes of landfills. It is a concept being introduced into integrated solid waste management recently. It includes recovery of soil masses and processing of excavated material from old landfills to recover recyclable materials and to reduce landfill space. It is also possible to recycle various materials and to recover energy from the incompletely degraded waste in incineration plants, or to produce biogas if the material should be landfilled again in a more modern landfill.

The materials that can be of interest for recovery are:

- wood for the production of wood chips
- bricks, stone and mortar material for road construction
- concrete waste for crushing into base material for roads, and
- metals such as iron, copper, aluminium, etc.

## 2.2.4 Compression and settlement of landfills

A schematic diagram illustrating the settlement potential versus time in a landfill area is presented in Fig. 9. According to Fang (1995a), Terzaghi's one-dimensional consolidation theory covers only a part of this settlement behaviour, because the theory is based on loading, i.e. mechanical energy. In landfill areas, the decomposition process involves multi-media energy fields including biological and physical-chemical processes. The current practice of settlement prediction is still based on the Terzaghi theory with modifications to overcome the environmental effects on future settlement.

Sowers (1973) suggested that continuing settlement of landfills is analogous to secondary compression of soil. The settlement with respect to time and depth of fill was described by him as follows:

$$\Delta N = \alpha \frac{N}{1+e} \log\left(\frac{t_2}{t_1}\right) \quad (1)$$

where

$\Delta N$  = total settlement (m)

$\alpha$  = coefficient which depends on field conditions

$\alpha$  = 0.09e (for conditions favourable to decomposition)

$\alpha$  = 0.03e (for unfavourable conditions)

$N$  = fill depth (m)

$e$  = initial void ratio

$t$  = time (years)

Yen and Scanlon (1975) suggested that settlement rate can be computed by the following equation:

$$m = \frac{\alpha}{1+e} \frac{N}{t-1} \log(t) \quad (2)$$

where

$m$  = settlement rate (feet per month)

$t$  = time elapsed (months)

Other notations in Eq. (2) are the same as defined in Eq. (1).

Due to the nature of the problem, the settlement analysis of landfills cannot be solved by mathematical equations. Semi-empirical methods such as equations (1) and (2) may be the best approach at the present time.

The settlement of landfills continues gradually after closure, due to the long decomposition time

of organic material. The theory of one-dimensional compression and consolidation is generally used in the estimation of the settlement (Oweis and Khera 1986; Saarikoski *et al.* 1981). The calculation of settlement, however, has been developed during the last few years. Edgers *et al.* (1992) have developed a so-called biological model for the calculation of settlement in a landfill. It is a mathematical model based upon both soil creep processes and bacterial growth kinetics. Bacteria are assumed, after an adjustment period of slow growth, to increase exponentially with time. A comparison of the field settlement data with model calculations shows good agreement. This suggests that the biological model may be useful for predicting long-term settlement data in landfills.

Sohn and Lee (1994) have presented a prediction method of long term settlement of landfills. According to their results, landfills undergo settlement at a significant rate under self weight for several decades. The model parameters were obtained through analysis of reported long term settlement data. It is shown in their research that the settlement rate result is uniquely determined in terms of the height and age of the fill.

According to Crawford and Smith (1985), general experience has shown that a waste layer compacted to an average density of about  $0.6 \text{ t m}^{-3}$  will probably compress 10 % or less. Most compressive settlement will occur within 10 years after the placement of the waste, although the settlement may not be finally completed for up to 30 years.

According to the Frantzis (1991), the total compression of wastes is 25 % of the total height of the landfill and most of it happens within 10 years.

Kissida (1991) reported the settlements of the greatest landfill in the northeastern part of the USA (Danahy Park, Cambridge, Mass.). The settlement of the landfill was found to develop logarithmically. It means that on average 25 % of the settlement develops within 6 months, 50 % within 5 years and 100% within 20 years.

The settlement of the foundation of the landfill can be considerable. According to Petäjä (1985), the settlement of the Iso-Huopalahti landfill in Helsinki was 3.5 m. It is built on soft clay, of a thickness of 15 m. In the peat areas relative settlement can be even more.

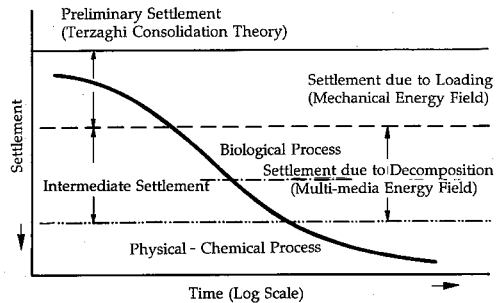


Fig. 9. Schematic diagram illustrating settlement versus time for a degradable material (Fang 1995a).

According to Scherbeck and Jessberger (1993), the centrifuge model tests suggest that deformed compacted mineral liners are no longer effective hydraulic barriers when cracks occur. Depending on the plastic behaviour of the liner material, tension cracks may appear, leading to an uncontrolled leakage through the liner; presence of overburdening loads will suppress this tendency. Cressman *et al.* (1992) conducted a laboratory investigation into the effects of subsidence-induced distortion on the hydraulic conductivity of unreinforced finegrained landfill covers or caps. The problem setting, mechanical models and behaviour of soil under flexure and tension are discussed. Based on the results of the study and observations made during the laboratory testing, several conclusions could be made. In general, subsidence distortion may have a significant effect on the hydraulic conductivity of unreinforced clay liners. The ability of the caps to resist the induced deformation relies on the shear and tensile strength of the cap materials as well as on their stiffness. These properties vary with the plasticity or clay content of the material. However, the strength is also influenced by its particle structure which is controlled by the compaction moisture content and furthermore, variations in tensile strength, shear strength, and stiffness with moisture content are not coincidental.

### 2.2.5 Compaction of landfills

According to Fang (1995a), among the factors relating to the stability and safety of landfills, the compaction control during the waste disposal process and the slope stability of a landfill during and after construction are the most important from

an engineering point of view. Further consideration of these two aspects is included together with suggested methods for the improvement of the effectiveness of the stability and landfill sites.

The "old fashioned" approach to waste disposal is when waste is delivered daily by truck and dumped into a landfill site. In some cases it is spread to make a thin layer, mixed with some earth material and compacted by conventional compaction equipment. This is done to cover up an unattractive landfill site or to minimize odour or to prevent animal and bird vandalism.

Compaction or densification is a simple and low-cost mechanical process for all types of construction. The main purpose of this process is to change loose material into a denser state for the following reasons:

- to reduce future settlement
- to increase bearing capacity
- to increase shear strength
- to reduce hydraulic conductivity.

In a landfill area when proper compaction is applied it can also reduce the potential fire hazard. The smaller the amount of air that is trapped in the landfill the smaller is the potential for combustion of the waste.

The process of surface compaction plays an important role in stabilizing the landfill. However, it requires planning during the waste disposal process period:

- waste comes in all types and it cannot be uniformly distributed in the whole landfill. However, within limits, it can be distributed uniformly within a layer (Fig. 7a)

- with non-uniform spreading the heavier items should be dumped close to the centre of the landfill for the purpose of controlling the stability of the fill (Fig. 7b). It is good to avoid dumping them around the edges of the landfill (Fig. 7c).

Petäjä (1985) reported the results from compaction tests of household wastes. The steel wheel compactor was a TANA S 8. In the test, there was not much additional compaction after 4 compaction runs. The number of the runs depended on the thickness of the waste layer. For waste layers less than 1 m, 4–5 runs were needed. For waste layers between 1.5–2.0 m, 6–8 runs were needed. According to the results, waste layers over 2.0 m must not be used, if efficient compaction is the aim.

### 2.2.6 Hydraulic conductivity of wastes

Hydraulic conductivity of landfill waste materials can greatly vary. According to the studies of the EPA (1983), the hydraulic conductivity of waste varied between  $10^{-3} \text{ m s}^{-1}$ – $10^{-7} \text{ m s}^{-1}$ . These hydraulic conductivities did not include any background information on waste characteristics, for example, the state of compaction. According to Fang (1983), with waste specimens of different compaction degrees, it was found that the hydraulic conductivity of waste varied between  $1.5 \cdot 10^{-4} \text{ m s}^{-1}$ – $7.1 \cdot 10^{-8} \text{ m s}^{-1}$ . Dry unit weights varied in the range of  $6 \text{ kN m}^{-3}$ – $11 \text{ kN m}^{-3}$  and they correlated well with the hydraulic conductivities.

According to Canziani and Cossu (1989), the range of hydraulic conductivity values varied from

**Table 2.** Summary of hydraulic conductivities of landfill wastes according to different sources.

Hydraulic conductivity $\text{m s}^{-1}$	Obs.	Source
$10^{-3}$ – $10^{-7}$	Background information about wastes not known	EPA (1983)
$1.5 \cdot 10^{-4}$ – $7.1 \cdot 10^{-8}$	Different compactions, unit weight $6 \text{ kN m}^{-3}$ – $11 \text{ kN m}^{-3}$	Fang (1983)
$10^{-4}$	Non compacted waste	Canziani and Cossu (1989)
$10^{-6}$	Compacted fine waste	Canziani and Cossu (1989)
$5.9 \cdot 10^{-5}$ – $4 \cdot 10^{-4}$	Heavily compacted landfill	Ettala (1987a)
$2.1$ – $2.5 \cdot 10^{-3}$	Slightly compacted landfill	Ettala (1987a)

$10^{-4} \text{ m s}^{-1}$  for non-compacted waste down to  $10^{-6} \text{ m s}^{-1}$  for fine compacted waste. Similar values have been observed also by Ettala (1987a). According to him, a field investigation on infiltration and hydraulic conductivity were carried out on two different landfills differing in their disposal technology. At both sites the infiltration rate mostly exceeded  $1 \text{ mm min}^{-1}$ , and surface runoff was small. The estimated saturated hydraulic conductivity of the heavily compacted landfill was  $5.9 \cdot 10^{-5} - 4.8 \cdot 10^{-4} \text{ m s}^{-1}$  and that of the slightly compacted landfill was  $2.1 - 2.5 \cdot 10^{-3} \text{ m s}^{-1}$ . Besides, depending on the disposal technology, the hydraulic conductivity also varied between different parts of the same landfill. Table 2 shows, in summary, hydraulic conductivities of landfill wastes according to different sources.

In summary, the hydraulic conductivity of wastes can very much vary due to the composition of various components, compactability, contribution of daily cover, moisture absorption, age and state of decomposition. Almost in all investigations, one has obtained a value for the hydraulic conductivity of waste which can be classified, according to Helenelund (1979), to the range of medium hydraulic conductivity. Hydraulic conductivity has significance for the generation of leachate water and it is also important in the design of surface structures.

### 2.2.7 Landfill gas

#### Formation of landfill gas

Landfill gas must be considered in the surface structures due to its effects on vegetation, buildings and also for utility use. Landfill gas results mainly from the anaerobic decomposition of organic material in anaerobic processes. The main components of landfill gas are methane and carbon dioxide, and it also contains a little nitrogen and oxygen. Methane is a colourless and odourless gas. The foul smell of landfill gas *insitu* is caused by mercaptanes and hydrogen sulphide.

According to Crawford and Smith (1985), waste is aerobic immediately after tipping, i.e. air pockets exist in the fill. The initial decomposition of the waste is via aerobic biological processes. Bacteria do not grow in dry conditions, so biodegradation only starts when the landfill is moist. The waste inherently contains moisture but this may be

increased due to wet milling or because the waste has been exposed in the rain at a transfer station. Once biodegradation has started, the oxygen in the tip is soon exhausted. As no free oxygen replenishment is available, the tip becomes anaerobic.

According to Pipatti *et al.* (1994) and Pipatti (1994), landfills and treatment of waste waters cause a considerable part of methane release in Finland. Half of the methane release into the atmosphere caused by human activity is from landfills and waste water treatment plants. However, the release estimation is uncertain. The releases may be even greater. On the other hand there are also opinions, based on conditions in Finnish landfills, that suggest methane emission may be smaller (Ettala *et al.* 1988a; Salmikangas and Laukkarinen 1990).

All methane does not go into the atmosphere because oxidation of methane to carbon dioxide and water occurs in the surface layer. There are different opinions on the amount of oxidation that takes place. According to Thorneloe (1993), methane coming out from cracks in the landfill spends such a short time in the surface layer that there is no time for oxidation. According to Bogner and Spokas (1993), it was proved in laboratory research that a maximum of 10 % of methane oxidized in circumstances that simulated the conditions of the landfill.

On the other hand, in tests made in the Netherlands, it was proved that bacteria can oxidize almost all methane which is leaking from earthgas tubes. Since a part of the methane oxidizes in the surface layer anyway, it is useful to study the use of compost or other material as a biofilter on the surface of the landfill especially on small landfills. On a global level, methane emission from landfills to the atmosphere is supposed to be 8–18 % of all the methane released into the atmosphere (Bingemer and Grutzen 1987).

Landfill gas containing methane is explosive at an atmospheric concentration of 5–15 % by volume. If such quantities accumulate in buildings which are on landfills, there is the likelihood of an explosion. In UK there have been several such explosions. In Finland such an explosion has occurred on the Mankkaa landfill in 1977 (Saarelainen, S. 1990, personal communication, Technical Research Centre of Finland). In Turkey there was a similar explosion in 1993 and several people were killed. (Güler and Avci 1995).

According to Ettala *et al.* (1988a), the quality of waste, gas, leachate and water was examined at five landfills in southern Finland. The methane contents

of the gas were low, 22 % vol. The moisture content and organic matter fraction of the waste were lower than the optimum for the methanogenic phase, which can be attributed to the use of too much covering soil. The concentrations of chlorinated hydrocarbons in the gas were well below the threshold limit value. The leachate should be analysed for estimates of the pollutant load on the receiving waters. The quality of the water in the waste indicates the degradation stage of the waste and reveals sources of groundwater pollution.

Landfill fires are common in landfills in Finland. In 1987–1989, there were approximately 360 fires annually. Toxic organic compounds may be released in landfill fires (Viatek Tapiola Oy 1993).

### *Effects of landfill gas on buildings and vegetation*

The problem of landfill gas emissions from landfills is associated with buildings and vegetation. Where possible, gas-generating fill should be removed from below any proposed building and replaced with inert material, this also answers the question of settlement. If it is not possible to remove the waste, the design and the actual construction of the building should be such that gas is prevented from entering the building (Crawford and Smith 1985).

According to Matsufuji *et al.* (1991), an old landfill was converted to a plot for a junior high school in Fukuoka, Japan. The procedure of site investigation for collecting data on the characteristics of the land for new use is presented in the research. Also, different measurements were taken for research into ground subsidence and corrosion. This case study is one of the first investigations of this kind in Japan and is regarded now as the standard procedure to take for the land of an old landfill.

Clark (1994) has researched landfill gas protection measures for industrial developments. In his research, types of gas protection measures for industrial buildings are reviewed and the criteria for selecting a particular type are discussed together with a brief summary of currently available guidelines in the UK. Examples are given of the various components of a system including membranes, vented granular blankets, undercrofts, passive and active venting, instrumentation and control systems and precautionary gas detection inside the building.

Landfill gas has the following main effects on vegetation (Crawford and Smith 1985):

- it can destroy soil structure and causes poor drainage,
- it can be toxic to most plant species and
- it can cause oxygen depletion which results in reducing conditions.

Landfill gas migrates upwards into overlying soil and also horizontally into the surrounding ground. A gas collection system should be installed beneath the waste material or the restoration should be delayed until gas production declines to an acceptable level, typically 5–10 years after tipping.

Duell *et al.* (1986) have investigated the effects of landfill gas on vegetation. They found out that where grasses fail, the planting of trees without a gas barrier can not be attempted. The success of grass growth does not guarantee tree survival anyway. In the absence of a methane or carbon dioxide detector, the foul odour and dark appearance of deeper soil are good indicators of anaerobic soils that will not support plant growth. The rust-red line of iron oxide delineates the aerobic soil from anaerobic soil below.

### *Utilization of landfill gas*

Finnish landfills produce yearly on average 5–12 m<sup>3</sup> landfill gas per ton of waste during a period of 20 years (Väisänen, P. 1994, personal communication, M.M. Karanoja Ltd.). After that period the production becomes weaker but continues for about 50 years. During this period of time landfills produce on average 150 m<sup>3</sup> gas per ton of waste. However, the circumstances at the landfill have a great effect on gas production. The conditions are affected by the composition of the various waste components, their compactability, contribution of daily cover, moisture adsorption, age, state of decomposition and temperature and, for example, if the waste has dried, the gas production can be considerably less compared to moist waste.

In 1994 landfill gas production at the Vuosaari and Seutula landfills was about 5 m<sup>3</sup> gas per ton of waste. For energy production 40 % is used yearly. In the Seutula landfill the percentage used is higher (60–70 %) due to good surface structures, which are 2 metres thick.

According to Tanskanen (1992) and Pelkonen *et al.* (1992), the impermeability of the surface layer is very important in the collecting of gas. It was seen that after rain, when rain had sealed the surface layer, the effective radius of landfill gas

pumping was sometimes two times greater than during dry weather.

The duration of good gas production is estimated to be 20 years but it continues after that for about 30 years and so gas production continues for about 50 years in all.

Väisänen (1987, 1993, 1995) has dealt with the utility use of landfill gas in Finnish conditions and reported that there is great potential for a landfill gas utility in Finnish landfills.

Results of the methane, hydrogen sulphide and oxygen measurements conducted in this research at Iso-Huopalahti, Mankkaa and Vuosaari landfills are presented in App. 1. According to the results, methane was measured from several points of all landfills. There were no gas removing systems in the landfills. Also, the smell of landfill gas was observed in some parts of all landfills.

In summary, in the design and construction of landfill surface layers, the risks of landfill gas affecting vegetation and causing explosions in buildings can be prevented by using gas leading structures or by removing the waste which causes it. The impermeability of the surface layer is very important in the collecting of gas.

## **2.3 Materials used in surface structures of landfills**

### **2.3.1 The use of soil materials**

Natural soils are mostly used in the surface structures of landfills. They are often found in the landfill surroundings and they are also relatively inexpensive. In the design of surface structures, all the geotechnical aspects and factors which affect the growth of the vegetation should be taken into consideration. The hydraulic conductivity of the hydraulic barrier is the most important factor in the surface structures because its main purpose is to prevent the infiltration of precipitation to the wastes. Qualities of natural soils can be improved for example by bentonite, fly ash and bitumen. Also wastes, geomembranes, geotextiles, geosynthetic clay liners (GCLs) and bentonite mixes can be used.

According to Knox and Gronow (1993), there was always some amount of infiltration through surface structures made of clay. The amounts will increase if the clay dries. In 12 landfill studies, mainly in Europe and USA, it was seen that the infiltrations varied from 0–200 mm a<sup>-1</sup>. Mostly, infil-

tration was 10–150 mm a<sup>-1</sup>. By covering the clay, which prevents the clay from drying and by making a drainage layer which conducts infiltrated water away, it is possible to achieve a very slow rate of infiltration into the waste.

Sarsby and Williams (1995) have researched the selection of soils for compacted clay lining. Using a soil property database, an attempt has been made to correlate the influence of various soil parameters with hydraulic conductivity for soils compacted at optimum moisture content.

After the construction of a landfill the greatest danger to surface structures are cracks in the hydraulic barrier caused by settlements and frost action. Though a landfill may be compacted well, the decomposition of the organic material may cause displacements and settlements in the surface structure. According to Miller and Mishra (1993), the waste contents of landfill waste relies on the hydraulic characteristics of the liner system. One important failure mechanism for clay cover liners is the development of macro-pores, resulting from desiccation, freeze-thaw cycles, and animal activity. This type of failure can lead to additional problems with the synthetic liner and gas migration. Most important, however, is the additional volume of moisture that enters the waste through the macropore openings of the cover liner.

There are several numerical models currently capable of simulating moisture transport through cover liners and leachate percolation through the waste. However, the models, in general, do not incorporate the potential failure of cover liners and the resulting leachate generation. Therefore, predictions from such models should be reviewed cautiously. As such, it is likely that the models are most applicable to the early stages after placement. For later stages, the leakage estimates provided by these models are expected to underestimate the actual field condition. That is also the case in the Landfill Cover Approximation Model (LCAM). One solution to this can be geomembranes, geosynthetic clay liners and bentonite mixes, which endure great deformations without increase in the hydraulic conductivity and are much better than, for example, clay.

In this research some investigations concerning surface parts of closed landfills were made. In the weight sounding tests conducted at Iso-Huopalahti, Mankkaa and Vuosaari landfills, resistance of the tests varied considerably on landfills at different points and they could be classified, according to the

weight sounding tests, from loose to tight (Tie- ja vesirakennushallitus 1970). Difficulties in penetrating wastes, for example, pieces of concrete, made weight sounding tests difficult at almost all investigation points. Therefore, light multiple-use drills were not suitable for landfill investigations. Hydraulic conductivity of the surface samples (0–25 cm) at Iso-Huopalahti, Mankkaa and Vuosaari landfills varied by  $10^{-6.0}$ – $10^{-8.8}$  m s<sup>-1</sup>, water content by 15.3–86.9 % and dry unit weight by 8.6–16.5 kN m<sup>-3</sup> (App. 1).

In the moisture measurements, made by the neutron tube in this research at the surface parts of Iso-Huopalahti, Mankkaa and Vuosaari landfills, it was seen that the greatest changes in moisture in different seasons were in the surface layers of a depth of 50 cm at the top and on the slope of the landfills (App. 1).

Materials of closed landfill surface structures in the survey of closed landfills (App. 2) classified by the regional environment centres are presented in Table 3.

### **2.3.2 The use of industrial wastes and other similar materials**

Industrial waste materials or by-products may be worth investigating as cover components in certain areas where they are abundantly available and inexpensive. The greatest quantities of potentially useful inorganic industrial waste materials are generated in the mining and metallurgical industries, including mine and pit wastes, mill tailings, furnace slag and others. In general, the coarse-grained waste materials may be useful in the permeable and loadbearing portions of cover systems. The finer waste materials are usually not useful in cover systems because of their undesirable non-plastic properties.

According to Havukainen (1983), coal ash can be used in earth works as a substitute for uncrushed natural aggregates. Ashes can be classified by type as fly ash, dry bottom ash and dry bottom boiler slag. Planning, construction and control instructions are given for improving the conditions for the utilization of ashes. The data are based on the results of investigations and construction experiments made at coal-fired power plants in the city of Helsinki. Structures made of coal ashes possess good strength properties, and they are lighter in weight and afford better thermal insulation than

natural aggregates. The strength and loadbearing properties of the hardening type of fly ash improve with age, which enhances their value in the construction of demanding earth works..

Sarsby and Finch (1995) have had a preliminary experimental investigation into the utilisation of two readily obtainable waste materials to make a suitable alternative landfill final capping material for waste disposal landfill sites. The waste materials which were chosen because of their wide spread availability were, pulverised fuel ash and papermill sludge. By combining these two byproducts a material was obtained which came close to satisfying the requirements for a capping material, i.e. low hydraulic conductivity and plasticity. The addition of small quantities of bentonite to achieve complete satisfaction of the capping requirements, and produce a more workable material, was also investigated. The individual materials, and various mixes, were subjected to compaction, classification and hydraulic conductivity tests. The resultant data have been promising and used to identify suitable mix proportions for further research.

According to Bowders *et al.* (1987), two class fly ashes from power stations located in West Virginia were stabilized by adding various percentages of either lime or cement. Test specimens were subjected to compaction, unconfined compression, vacuum saturation durability and hydraulic conductivity tests. Results from the testing showed that adequate strength and durability can be achieved with sufficient stabilizer contents and curing. Hydraulic conductivity decreased with increasing amounts of stabilizer. The findings suggest that stabilised fly ash could serve as an alternative to clay soils in seepage cut-off applications in earthdams, impoundment liners, and landfill liners.

NCASI (National Council of Paper Industry for Air and Stream Improvement, Inc.) (1989) has studied the use of pulp and paper mill solid wastes in landfill cover systems. Based on the results of physical and chemical characterization, it is concluded that several of the sludges and one fly ash tested represent potential alternatives to clay for use as hydraulic barrier material in landfill covers. Two of these sludges have been selected for use in constructing hydraulic barrier layers in 2500 square foot landfill simulators located near NCASI's Central-Lake States Regional Center in Kalamazoo, Michigan. The simulators will allow the effectiveness of these sludges to be examined in the field over a period of time adequate enough



to verify their suitability as substitutes for clay in the barrier layer of landfill covers.

According to Zimmie *et al.* (1995), a paper mill sludge from a paper manufacturing operation was substituted as the hydraulic barrier for landfill covers in Massachusetts. The study investigates the geotechnical properties of the paper sludge. Paper mill sludges have a high water content and have a high degree of compressibility. Composed of 50 % kaolinite and 50 % organics, the sludge behaves like a highly organic soil. Paper fibres and tissues throughout the sludge created problems in testing, e.g. trimming and setting.

Triaxial shear strength tests were conducted on undisturbed samples. A large variation in the strength parameters resulted from the nonuniform mix of the sludge in the landfill. In general, laboratory hydraulic conductivity tests conducted on insitu specimens met the  $10^{-9} \text{ m s}^{-1}$  requirement for landfill covers. Freezing and thawing cycles increased the sludge hydraulic conductivity about one order of magnitude. Maximum hydraulic conductivity changes occurred within ten freeze-thaw cycles.

According to McAneny and Hatheway (1985) asphalt has been used in hydraulic barriers in USA. However experience with asphalt in cover systems is limited. In the survey of closed landfills (Table 3 and App. 2) it was found that in Finland asphalt was used on the surface structures of one landfill.

In summary, many wastes are usable in the surface structures of landfills. In the survey of closed landfills (Tab. 3 and App. 2) it was seen that in only some landfills were waste materials, such as ash and wastes of the forest industry, used on the landfill cover. Therefore in the future, research concerning the use of wastes in surface structures should be increased. In Finland, special research concerning the use of wastes from the pulp and paper industry should be started.

### 2.3. Geomembranes, geotextiles and bentonite

According to McAneny and Hatheway (1985), geomembranes have been used as pond and lagoon liners for several decades, but their use in cover systems is relatively new. Traditionally, the seams have been regarded as the weakest link in the geomembrane. However, high-quality seams

are commonly achieved by modern seaming methods and quality-control practices. Also, the consequences of small leaks are less serious in a cover generally overlain by unsaturated soil, than in a liner generally overlain by free liquid.

Geotextiles, or synthetic geotechnical fabrics, are the permeable counterpart of geomembranes. They are uncoated synthetic textile products that can be incorporated into engineered structures where a watertight structure is not desired. Geotextiles fulfill five basic functions: filtration, drainage, separation, reinforcement and armouring. Geotextiles may find applications in several portions of cover systems other than in the hydraulic barrier member for which geomembranes are suitable.

According to Hoeks and Ryhiner (1989), bentonite liners used for surface capping proved to be completely impermeable over a 3.5 year period in spite of large settlements. For surface capping Hoeks *et al.* (1987) recommended a bentonite content of at least 5 weight-% and a layer thickness of at least 15–20 cm. Higher bentonite contents are recommended for bottom liners, as bentonite liners are more permeable for contaminated leachate from a waste disposal site than for clean water.

Sjöholm *et al.* (1994) researched the effect of bentonite on the hydraulic conductivity of various different materials, which were moraine, sand and ash. It was seen that the best results were obtained with moraine, but differences were not great.

Daniel (1995), Forster (1995) Bishop and Carter (1995) and Wallace (1993), have dealt with the use of geomembranes and geosynthetic clay liners in the surface structures of landfills. They have reported among other things that differential settlement of compacted clay from uneven compression of underlying waste is almost certain to produce cracks within the clay. Geomembranes do not suffer as much from these problems, and geosynthetic clay liners are much better able to resist damage from freeze-thaw, desiccation, and differential settlement than compacted clay.

No landfill in the survey of closed landfills (Table 3 and App. 2) contained geomembranes, geotextiles, bentonite or geosynthetic clay liners in the surface structures. In future, the suitability of geomembranes, geosynthetic clay liners and bentonites in the surface structures of landfills in the Finnish climate should be researched.

## 2.4 Parts of surface structures of landfills

### 2.4.1 Background

Figure 10 presents a schematic diagram of the elements layer that may be found in a multilayered cover system. The elements are landfill gas control layer, filters, foundation layer, hydraulic barrier, drainage layer, biotic barrier and surface or vegetation layer. Not all elements may be required for a given site, but it is likely that cases may exist where all of the cover elements are required.

Chapters 2.4.2–2.4.8 deal with the structure parts of the cover system according to McAneny and Hatheway (1985). Chapter 2.5 deals with additional factors affecting the surface structure design, such as enduse of landfill sites, surface water management, frost action and snow removal. The requirements for the different structure parts were compared, among other things, to the results of the national survey of closed landfills with regard to surface structures (Table 3 and App. 2). Saarela (1994b, 1995, 1996a, 1996b) has studied the design of cover systems of landfills.

### 2.4.2 Landfill gas control layer

A gas-control layer intercepts gases produced by the wastes and directs them to the atmosphere via venting mechanisms, if any. Landfill gases are produced whenever biodegradable organic matter is buried.

To control landfill gases, it is desirable that a layer of coarse grained material be present. The coarsest gradation possible is desirable to inhibit the growth of a biomass of anaerobic slimes. Also glass waste can be used in the gas control layer. Pipe vents, with or without exhaust blowers and set in gravel packs to give a clear channel for the gas to flow, may be placed at regular intervals to vent the gases to the atmosphere.

In the survey of closed landfill (App. 2), it was found that only two landfills had landfill gas removing structures. Later, however, landfill gas collecting systems for utility use of landfill gas have been installed on several larger landfills in Finland.

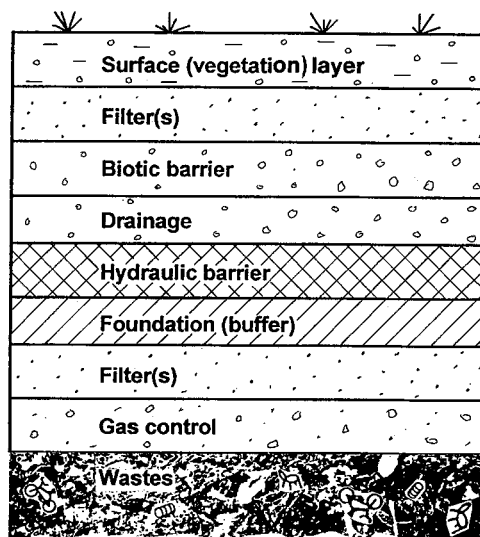


Fig. 10. Structure of cover system (McAneny and Hatheway 1985).

### 2.4.3 Filter layers

Filter layers separate fine materials from coarse materials and prevent clogging of the coarse materials by fine particles.

If a coarse-grained material is placed beneath a fine-grained layer, the fine grains may migrate and block the pores of the coarse layer. Such cases require a filter layer. Its function is simply to prevent unwanted mixing, while at the same time allowing fluids (water or gas) to flow freely.

Two types of filters may be used. One type of filter is a layer of carefully graded cohesionless soils (sands and gravels). Such graded filters are durable, have a long history of use and often can be made from readily available materials. Careful attention is required both to the gradation of the material selected and to the installation.

The other type of filter is a geotextile. These geotextile filters are relatively simple to install; however, they do not yet have a service history from which to predict long-term behaviour. As with granular filters, careful attention to the relation between the size of openings in the fabric and the size of soil particles to be separated is required.

In the survey of closed landfills (App. 2), it was

found that none of the landfills had filter layers. Slunga (1985), International Society of Soil Mechanics... (1987) and Tesfaye (1991) have dealt with filter criteria in earth structures and reported among other things, that soil filters have a history of long use but geotextile filters do not.

#### 2.4.4 Foundation (Buffer) layer

A foundation or buffer layer isolates the hydraulic barrier from the wastes and also serves as a strong base to support the rest of the system.

The foundation layer performs two important functions. It separates the hydraulic barrier from the wastes and thus acts as a buffer between them. Both, chemically and mechanically (by protrusions of waste containers, etc.) the wastes may damage the hydraulic barrier.

**Table 3.** Material of surface structures of closed landfills classified according to regional environment centres in the survey of closed landfills in 1990 (Saarela 1994a).

Regional environment centre <sup>x)</sup>	Material of surface structure												
	Waste soil		Sand and silt moraine		Gravel and		Clay		Humus soil		Moraine		Other
	Num.	Thickness m	Num.	Thickness m	Num.	Thickness m	Num.	Thickness m	Num.	Thickness m	Num.	Thickness m	
UUS	4 <sup>1,2</sup>	0.5–10 <sup>27)</sup>	1 <sup>3</sup>	1–5.0	2 <sup>4)</sup>	0.5–5	1 <sup>5)</sup>	1–5	–	–	1 <sup>6)</sup>	–	2 <sup>7,8)</sup>
LOS	8	1–20 <sup>27)</sup>	–	–	–	–	–	–	1	1–2	–	–	–
HAM	5	–	–	–	–	–	2 <sup>9)</sup>	1.0–2.0	–	–	1	–	1 <sup>10)</sup>
KAS	16	–	4	–	3	–	2 <sup>11)</sup>	–	1	0.1–0.15	–	–	4 <sup>12,(13,14)</sup>
ESA	19 <sup>15)</sup>	–	–	–	1	–	–	–	–	–	2	–	–
PSA	–	–	1 <sup>16)</sup>	0.5	–	–	1	1,0	–	–	3	0.8	1 <sup>17)</sup>
PKA	14	0.5–2	–	–	2	–	1	0,5	–	–	1	–	1 <sup>18)</sup>
LSU	11	–	–	–	–	–	1 <sup>19)</sup>	0.2–1.0	–	–	–	–	1 <sup>20)</sup>
KSU	2 <sup>21)</sup>	0.5	–	–	1	–	1 <sup>22)</sup>	0.6	–	–	–	–	–
KPO	11	1–2	–	–	–	–	–	–	–	–	–	–	–
PPO	4	–	2 <sup>23)</sup>	0.5–1	–	–	–	–	–	–	3 <sup>24)</sup>	0.5–1	1 <sup>25)</sup>
KAI	4	0.5–1	1	0.5	–	–	–	–	–	–	2	0.5–0.7	–
LAP	5	1–2	–	–	–	–	–	–	–	–	–	–	1 <sup>26)</sup>
Total	103		9		9		9		2		13		12

x) appendix 2, Fig 1.

- 1) also sewage sludge
- 2) vegetation layer made by blending soil and sludge
- 3) also waste soil
- 4) also vegetative layer
- 5) also sand
- 6) also humus layer as a vegetation layer
- 7) peat layer as a vegetative layer 30–100 cm
- 8) building rubble
- 9) also moraine
- 10) surface structures have been designed but not built
- 11) also waste soil on the other landfill
- 12) wood chips 20–30 cm
- 13) also soil and bark on two landfills
- 14) partly asphalt
- 15) also ash and waste wood
- 15) also ash and waste wood
- 17) road on the landfill
- 18) waste of saw industry, poorly covered
- 19) also waste soil
- 20) surface layers have been planned, hydraulic barrier 60 cm and vegetative layer of humus 10 cm
- 21) also sand
- 22) clay loam as a hydraulic barrier 60 cm and vegetative layer 60–100 cm
- 23) also waste soil
- 24) also waste soil on two landfills
- 25) wastes are uncovered, surface structures have been planned
- 26) wastes are uncovered, surface structures will be designed according to principles of arctic greenbuilding
- 27) waste soil storage area.

The second and equally important function is to serve as a loadbearing member to support the weight of the rest of the cover. The inevitable problem of subsidence within the wastes undermining the cover system may be mitigated by the foundation layer. The best materials for the foundation layer are coarse-grained, granular soils or their equivalents in the non-soil category. The soils should be thoroughly compacted, using appropriate compaction equipment for granular soils. Stabilization of the soil in the foundation layer may be advantageous.

In the survey (Table 3 and App. 2) coarse-grained excess soils on the closed landfills can be classified as foundation layers.

#### **2.4.5 Hydraulic barrier**

The primary function of the hydraulic barrier is to divert or impede the downward percolation of any water coming into contact with it. The ability of this layer to perform its function is critical to the success of the cover system.

Failure mechanisms which the hydraulic barrier might be prone to, are for example, mechanical and environmental. Mechanical failure especially needs to be guarded against during construction. Delayed mechanical failure might take place through the undermining of the hydraulic barrier from severe subsidence beneath it.

Environmental failure may be caused by freezing and thawing, waterlogging and drying, etc. Environmental failure may also come about through the attack of plant roots or burrowing animals.

Barrier materials include fine-grained, amended soils, asphalt and geomembranes, geosynthetic clay liners and bentonite mixes. Natural soils have the advantage of durability. They should be thoroughly compacted, although even with compaction, they cannot be made completely impervious. In practice differential settlements, uneven compression of underlying waste and frost, will almost certainly produce cracks within a hydraulic barrier made of clay and will increase the hydraulic conductivity. Bentonite mixes, geomembranes and geosynthetic clay liners are more able to resist these types of damage.

In the survey of closed landfills (Table 3 and App. 2), some landfills had cover structure materials that could be classified as a proper material for a hydraulic barrier. However, their function as a proper hydraulic barrier cannot be sure due to the

lack of proper compaction and other structure parts, and also because structures of landfills have in general not been designed and constructed properly. Chapter 2.6 deals with the requirements for hydraulic barriers in Finnish conditions. Chapter 5 deals with the quantity of infiltration of annual precipitation into waste with hydraulic barriers having different hydraulic conductivities analysed numerically with the Landfill Cover Approximation Model (LCAM).

In future, methods of stabilization to improve the quality of poor soils for use in the hydraulic barrier, should be developed.

#### **2.4.6 Drainage layer**

A drainage layer intercepts downward-percolating water and conveys it laterally out of the system. The function of the drainage layer is to intercept water that has entered the cover system as infiltration and to conduct it away to one or more safe disposal outlets. In so doing, the drainage layer prevents water from building up or sitting for extended periods on the hydraulic barrier and thus relieves the load on the latter. The drainage layer will consist of a blanket of free-draining sands and gravels and a collection/transport system will form a network of varying complexity depending on the site. The exits from the collection system should be designed with care to prevent erosion from concentrated flows.

In the survey of closed landfills (Table 3 and App. 2) none of the landfills had drainage layers. Chapter 5 deals with the effects of the drainage layer on the quantity of infiltration of annual precipitation into waste analysed numerically with the Landfill Cover Approximation Model (LCAM).

#### **2.4.7 Biotic barrier**

A biotic-barrier layer (largely conceptual at present) hinders plant roots and burrowing animals from disrupting the layers below, particularly the hydraulic barrier.

The need for a biotic barrier layer arises from the threat of damage to the hydraulic barrier from plant roots and burrowing animals. Research results according to McAneny and Hatheway (1985), indicate however, that cobblestones, brick rubble or other large particles appear

to be effective for domestic grasses and legumes. Weeds may have to be removed from a cover system for a variety of reasons, and in some cases, the use of insecticides may have to be considered.

In the survey of closed landfills (Table 3 and App. 2), none of the landfills had a biotic barrier. Experiences with biotic barriers are in practice limited and, therefore research into the behaviour of biotic barriers in Finnish conditions should be started.

#### 2.4.8 Vegetation layer and landscaping

A well-designed controlled plant community on a landfill cover will prevent erosion, expel water from the cover system through evapotranspiration and improve site aesthetics. Vegetation is usually very cost-effective. However, fertile soils are rarely available at landfill sites, and it is necessary to work with the inferior soils that may be present. The great toxicity and high temperature of landfills have often been the reason for unsuccessful plantation.

The landscaping of a landfill depends on its size, location and enduse. A landfill near a large city which is designed for recreational use needs totally different landscaping from a small remote landfill. However, landscaping aims for all types of landfills should be to remove all signs of the former landfill and even to improve the original site.

Ettala (1987b, 1988a, 1988b) and Ettala *et al.* (1988b) has conducted wide and thorough studies in Finland on the landscaping of landfills. The main results concerning vegetation on landfills are:

- On landfills still in operation, plant coverage was low, only 25 %. Woody plants were scarce and natural forestation took place slowly at landfills no longer in use. The main reasons for this were disturbance of the vegetation caused by vehicles and dumping of new waste and cover soil, and an unsuitable or insufficient cover material.
- Good growth was achieved with at least 10 cm of cover soil for grass and a sufficiently fine-textured substrate, preferably silt or moraine. Organic material in the substrate had a growth-stimulating effect.
- In order to increase the present vegetation coverage of landfills, planting is needed. Most of the short-rotation tree plantation at six landfills developed, with even the six-year-old stands growing satisfactorily.

*Salix aquatica* was the most productive species

and therefore had the best increase in evapotranspiration. *Salix viminalis* also developed well, but had a lower biomass production, and in one case was eaten by hares. *Populus rasumowskyana* and *Betula pendula* proved to be possible alternatives for landscaping a site.

- Irrigation with leachate not exceeding 500 mm during the growing season had a beneficial effect on the growth season and had a beneficial effect on the growth of short-rotation plantations. Nonirrigated stands lost their leaves early during a dry summer period.
- The best growth was achieved on a substrate with a high humus content and a thickness of at least 0.2–0.3 m. Five years irrigation with leachate raised the substrate salinity. This did not cause any disturbance to the growth because the salinity was kept low enough by occasionally using high-intensity irrigation to wash the substrate.
- The cost of short-rotation plantation covering 30–50 % of the site can be estimated to be 10 percent of the total capital and maintenance cost of a landfill. This estimate can be considered modest compared with, for example, the costs of other leachate treatment methods or drains to a sewage treatment plant.
- The average above-ground biomass production of a *Salix aquatica* plantation irrigated with leachate was 2.3 kg dry matter m<sup>2</sup>a<sup>-1</sup>, which is one of the highest values recorded in Finland. The costs of establishment and management of the plantation can be regarded as the cost of waste management, and the willows cultivated at landfills can be a profitable source of energy if suitable equipment for chipping and wood chip heating plants are available.

The effectiveness of a soil for supporting vegetation is determined by grain size, pH, organic matter and nutrient content. Many other factors play necessary though less critical roles. Design consideration for waste cover systems should be given to whatever soils are locally available. In addition, waste materials such as sewage sludge, fly ash and liming agents, should be considered to improve the fertility of the available soil materials.

Appropriate tests can be made on the soils proposed for use in the vegetation layer at a testing laboratory. Soil tests can indicate whether the soil material is acid, saline and sodic, excessively drained, poorly drained, wind erodible or contains dispersive clay. The thicker the vegeta-

tion layer, the more stable it will be and the better it can support desirable naturally deep-rooted plants. Among the factors to be considered is the need to retain enough moisture in the surface layer to sustain vegetation through dry periods.

With the blendings of bark and domestic sewage sludge, good results have been achieved in willow plantation on landfills (Ettala 1988b). According to Lahtinen (1982a, 1982b, 1982c), raw sewage sludge is not good, but needs additional treatment to be suitable in greenbuilding. The treatment methods are, for example, putrefaction, decaying, compaction, stabilization and drying.

According to Wise *et al.* (1994), a series of standard soil tests were performed on mixtures of municipal sewage sludge compost and selected soils to determine the feasibility of using the composted sludge as landfill cover material. One compost was produced by using wood fly ash as the bulking agent, while the other was produced by using wood chips as the bulking agent. At the time of testing, both soils were being used as landfill cover. The results indicate that municipal sludge composts can be used effectively as a soil amendment for landfill covers. However, compost using a fly ash bulking agent exhibits greater strength when used alone or in combination with soil, compared to compost produced using wood chips as a bulking agent. Additionally, the coefficient of hydraulic conductivity of the soils was significantly decreased with the introduction of both types of composts.

According to Neumann (1984), the minimum thickness of the needed soil layer for trees is 150 cm, 50 cm for bushes and 30 cm for grass.

According to Vainio (1984), the best species on landfills are willows, alders, silver birch and low root grass, which also tolerate some amount of methane.

In the investigations of Dobson and Moffat (1993) there were four main areas of concern regarding tree planting on landfill sites, which were: a) whether trees can successfully be grown on the relatively hostile environment of a landfill site, b) whether tree roots are likely to penetrate through a landfill cap, c) whether tree roots are likely to cause desiccation cracking in a clay cap, and d) whether there is an unacceptable risk of windthrow.

Some of the main findings and recommendations resulting from this research are outlined below.

- Despite fears on the contrary, trees can survive and grow well on landfill sites. Nevertheless, poor growth and sometimes outright failure have been quite common, although failure has often been as much a result of factors such as soil compaction, shallow soil, waterlogging and drought, as well as factors directly related to the landfill, e.g. landfill gas and leachate.
- The majority of tree roots are found within the upper 1 m of soil on undisturbed woodland sites. Most trees have root systems reaching a maximum depth of between 1 and 2 m, though small roots up to 5 m deep have been recorded in the UK. Rooting depth is controlled primarily by soil conditions; vertical development is prevented by unfavourable soil conditions such as compaction and lack of oxygen. Thus, tree roots will not penetrate through high density polyethylene (HDPE) sheets, and are unlikely to penetrate into compacted clay with a very low oxygen concentration. This applies equally well to the taproots of trees as to any other roots.
- The risk of windthrow can be minimized by encouraging the development of a well-formed root system, through the provision of a sufficient depth of loose soil, by planting trees which are relatively small at maturity, or by managing woodland using the coppice system.
- Tree roots are not considered to be a primary cause of desiccation cracking in a clay cap.
- The irrigation of trees with leachate can also help to attenuate its strength and reduce its volume. Irrigation with low strength leachate can stimulate tree growth, but high strength leachate (specific electrical conductivity of 0.2–0.4 S m<sup>-1</sup>) is likely to cause injury.
- To protect the cap from damage or desiccation, a suitable depth of soil cover must be provided. For woodland establishment it is recommended that a minimum thickness of 1 m should be provided above an HDPE sheet cap, and 1.5 m above a clay cap.
- It is vitally important that site soil compaction is avoided where woodland is to be established on a landfill. Soil or soil-forming materials should therefore be placed by loose-tipping. If loose-tipping is not possible, or reconsolidation takes place after soil placement, cultivation by deep ripping should be carried out in the season before tree planting.

Gilman *et al.* (1985) have dealt with standardized procedures for planting vegetation on completed

landfills. In their research standardized procedures were developed for those charged with establishing a vegetation cover on completed landfills. Special problems associated with growing plants on these sites are discussed, and step-by-step instructions are given for converting a closed landfill to a variety of end uses requiring a vegetative cover. Procedures are outlined for planting landfills with either limited or adequate funds.

Vegetation has a great significance in the prevention of erosion. According to the field observation in the survey of closed landfills (App. 2), though scientific vegetation observations were absent, it was already seen clearly that on gentle slopes great erosion damage developed, even in a short time, if there was no erosion-control vegetation. Erosion-control vegetation should be planted immediately before the highest expected rainfall. If the optimum planting dates cannot be observed, the area should be seeded with one or more fast-growing annual species. Irrigation can be used as a temporary measure.

According to Hytönen and Ferm (1984), *Salix aquatica* should grow to be at least 3 cm thick for energy tree mass.

According to Ferm (1990), the values of the nutrient contents in plants are much higher at the beginning of the growth period and decrease quickly. The timing of the sampling is very important when nutrients are analysed from plants.

Forsius and Assmuth (1990) researched the use of sludges and ashes from the Finnish forest industry. According to their results, they can be used, for example, in greenbuilding and in soil improvement.

Fang (1995b) has dealt with bacteria and tree root attack on landfill liners. He has presented the mechanisms of soil-bacteria interaction and soil-root interaction in landfill areas. Control or minimization of these attacks on landfill liners are presented in his research.

In the survey of closed landfills (App. 2), it was seen that most landfills were without proper vegetation and landscaping. In this research the nutrient content of surface samples of Iso-Huopalahti, Mankkaa and Vuosaari landfills were analysed (specific electrical conductivity, acidity, nitrate nitrogen, phosphorus, potassium, calcium and magnesium and boric). Results of the analyses were compared to the Finnish recommendations on greenbuilding. It was clearly seen that almost all samples needed several different nutrient additions to support vegetation (App. 1).

Chapter 5 deals with the effects of vegetation on the quantity of infiltration of the annual precipitation into waste, analysed with the Landfill Cover Approximation Model (LCAM).

In summary, vegetation and landscaping should be one important part of the closure of a landfill because they reduce infiltration by evaporation and help a landfill to merge in with the surroundings and returns the land into usage.

## 2.5 Additional factors affecting to design of surface structures

### 2.5.1 Enduse of landfill sites

According to Dunn (1995), closed landfill sites are increasingly being utilized as development properties to construct and operate a variety of different facilities with many types of landuse. Successful project design and development requires careful and thorough evaluation of site conditions and redundant design features for buildings and infrastructure. Operations and scheduled maintenance must also be carefully planned and response actions considered. Major elements of post-closure landfill development require design consideration: 1) landfill closure and waste containment; 2) control of landfill gas and leachate; 3) settlements; and 4) civil infrastructure constraints. Health and safety considerations must also be incorporated into all aspects of the project. Settlements of waste materials are difficult to predict, but empirical and conservative evaluation seems to be the most suitable technique. Techniques are available to reduce settlements; however on most projects deep foundations, usually driven piles, are used to support all lightly loaded structures. Civil infrastructure design generally follows a four step design process that starts with an analysis of historical records and geotechnical data. This is followed by definition of site constraints and boundary conditions. Civil works are then designed for the predicted total and differential settlements. Finally, future inspection and maintenance requirements are developed to deal with the uncertainties of actual performance.

Oteo and Sopea (1995) have dealt with deep treatment of uncontrolled urban landfills for the construction of a high capacity road system.

Crawford and Smith (1985) have researched restoration and enduse problems of landfills in

England. According to their results, a residential area is the most expensive enduse for a landfill, and for example, a recreation area is much cheaper.

In the survey of closed landfills, the majority of landfills did not have an enduse (App. 2). App. 1 deals with the results of the pilot investigations concerning the enduse of landfills conducted in this research. The investigations concerned the measurement of radon emanation, chlorinated phenols and polyaromatic compounds from the samples of Iso-Huopalahti, Mankkaa and Vuosaari landfills. According to the results, it was seen that the radon emanation was on the same level as typical radon emanation in loose soils in southern Finland and there was nothing alarming concerning radon on the landfills in question. Also values of polyaromatic compounds and chlorinated phenols were low and they were not a risk for the landfills in question.

In future, the enduse of landfills should be made more effective for the landuse and surroundings. Landfills should be a more active part of the landuse of a community. In selecting an enduse, the main principle is that landfills near residential areas and cities are most suitable for outdoor life and recreational purposes and landfills far from residential areas are suitable, for example, for industrial and motor sport activities.

### 2.5.2 Surface water management

According to McAneny and Hatheway (1985), surface water management refers to all features concerned with the management or control of runoff. The goal of surface water management is to handle runoff in a controlled fashion; that is, to conduct it off the site in such a way that it does not erode the cover system.

Surface water management involves land grading, waterways, diversion structures, checking dams and outlet structures. Land grading, which is the reshaping of a site's existing topography, is carried out in accordance with a plan based on an engineering survey and layout. The steepness of cut and fill slopes should be controlled according to established principles. Reverse-slope benches and diversions may be used to limit maximum overland flow distances. The land grading plan must be integrated with waterways and diversion structures to form a coherent overall drainage system.

According to Ettala (1987a), however, surface runoff is small on Finnish landfills due to the low

intensity of rainfall, small slopes on landfills and displacements and cracks on the surface layers of landfills.

Erosion observations made in the survey of closed landfills are described in App. 2. It was seen that on gentle slopes great erosion failures can develop in a short time if there is no vegetation to prevent erosion.

### 2.5.3 Frost action

The threat of damage from frost action in the Finnish climate must be taken into consideration in the cover system of landfills. The most serious damage is caused by frost heaving, the formation of ice lenses within the soil.

Formation of such lenses, and their collapse when they thaw and drain, could disrupt the cover system. Among the factors necessary for frost heaving to occur is the presence of a nearby water supply to sustain the growth of ice lenses. By providing proper drainage, the designer can ensure that such a water supply is not available and that frost heaving will not take place.

Zimmie *et al.* (1992) have researched the effects of freezing and thawing on the hydraulic conductivity of compacted clay landfill covers and liners. According to their results, an increase in the hydraulic conductivity of a fine-grained soil is due to freeze-thaw effects. The results range from an increase of approximately one order of magnitude to one and one-half orders of magnitude from the initial hydraulic conductivity to the final hydraulic conductivity. The results were similar for both samples, frozen and thawed at their moulding water contents and samples frozen fully saturated.

According to Chamberlain (1989), the increases in the coefficient of consolidation of the clay soils during freezing and thawing are due to the increases in the hydraulic conductivity. The structural changes that occur during freezing cause increases in the hydraulic conductivity. The most obvious structural changes affecting the hydraulic conductivity of the thawed clays are the shrinkage cracks that form during freezing.

Chamberlain and Gow (1978) have reported increases in hydraulic conductivity of a saturated clay of medium plasticity of roughly three orders of magnitude when freezing occurred at a water content near the liquid limit, and one order of magnitude for an initial water content just above the plastic limit.



Chamberlain and Blouin (1978) and Chamberlain and Gow (1978) have also found that the hydraulic conductivity increases in the direction normal to the direction of freezing and the increases were similar to the hydraulic conductivity increases in the direction of freezing. This is an important observation because it means that a drainage system can be placed in either direction to improve consolidation properties.

The results of frost measurements conducted in this research at Iso-Huopalahti, Mankkaa and Vuosaari landfills in the winters 1990–1992 are presented in App. 1.

Frost depth varied between 52–90 cm. According to the results, the frost depth at landfills was, on average, less than in natural areas. This is due evidently to the decomposition of organic material, which produces heat.

However, it must be noted that the frost depth can vary greatly in different landfills due to the age of the landfill, type of waste, depth of snow, etc. which have effects on the temperature of waste. The effect of the temperature of wastes on the frost depth must, if needed, be measured or calculated, because of the new land fill technology aims e.g. to enlarge, centralize and increase the height of landfills. It can be supposed that the temperatures of landfills are in future higher which will decrease the frost depth. Temperature of landfills measured in USA were about +40 °C and in UK about +50 °C (Peggs, I. 1994, personal communication, I-Corp. International). Differences were caused by the different composition of wastes.

Saarelainen (1992) has researched the modelling of frost heaving and frost penetration in some observation sites in Finland. The purpose of his study was to monitor frost heaving and frost penetration at six observation sites in Finland in 1982–1984. Frost heaving was also studied in the laboratory with frost-heave tests carried out on undisturbed specimens. The observed freezing behaviour was compared with the climatic conditions. A calculation model developed in his research based heat balance at the freezing front was tested for the estimation of frost heave and frost penetration.

In future, research into frost protection of landfill surface structures in the Finnish climate should be done. For example, the effect of the warming produced by the decomposition of organic material on the frost depth and the thermal insulation of surface structures should be of special interest.

## 2.5.4 Snow removal

Snow removal can be recommended from the point of water protection and economy. According to Etala (1986, 1987a) infiltration can be decreased by moving the snow cover on the landfill to the other side of the surrounding ditches. In this way the pollutant load on the receiving waters could be diminished. This would also decrease the cooling effect of infiltrating melt water on the landfill. The cost of removing the snow cover is small compared with the savings due to the reduction in the size of the leachate basin needed and in the amount of leachate to be treated. The snow cover can be removed from a coppiced *Salix* stand without notable damage to the plants. Leachate treatment based on short-rotation tree plantations and removal of the snow cover costs only half as much as treatment at a municipal wastewater plant.

In the survey of closed landfills (App. 2), attempts to reduce the amount of leachate water with snow removal were not made at any landfill.

Chapter 5 deals with the effects of snow removal on the quantity of infiltration of annual precipitation into waste, analysed with the Landfill Cover Approximation Model (LCAM).

In summary, the removal of snow from landfills is not a common practice at the moment in Finland. In the future, it should be taken into consideration as an inexpensive, and easy way to reduce infiltration to waste, whenever possible. However, snow removal depends often on local circumstances because, for example, landfills can be situated at high locations and then wind can blow snow away. In some cases it is also possible to take snow into consideration in the frost protection of the hydraulic barrier.

## 2.6 Choice of surface structures for covering landfills in Finland

### 2.6.1 Background

In Finland, the waste management policy at the beginning of this study in 1990 was in a such situation that the closing of landfills had then just started to radically increase and there were no standards for covering landfills. There was a pressure and an urgent need for surface structure types for practical use by landfill owners and environmental authorities.

Therefore, in cooperation with the National Board of Waters and the Environment (from 1.3.1996 the Finnish Environment Institute), the Helsinki Metropolitan Area Council and Viatek-Tapiola Oy, different types of surface structures for different landfills were chosen (Viatek Tapiola Oy 1991, Saarela 1994a, 1994b, 1995). One base for the choice of the surface structures was the survey of closed landfills (App. 2). In the survey it was investigated how closed landfills were covered and recommendations made for measures to improve the practice of the landfill coverage for Finnish conditions. The following sources were also used in the choice: Stief (1989), Jessberg and Klos (1992), German Geotechnical Society (1993), Lechner (1989), Pacey (1989), Forster (1995), McAneny and Hatheway (1985), Lutton *et al.* (1979), EPA (1989) and Dwyer *et al.* (1986).

The group of experts from the above mentioned parties selected five different types of the surface structure shown in Fig. 11. The author was the head coordinator of the group from the National Board of Water and the Environment. They have already been taken into wide use due to the great need for such structure types, e.g. by the requirements of environmental authorities for industrial and municipal waste management plans.

## 2.6.2 Types of surface structures

### Background

Principles of design of cover systems are dealt with in Chapter 2.4. In the survey of closed landfills (Table 3 and App. 2) it was seen that landfills were not properly planned and constructed. It was also seen that their size and location differed very much from each other. Landfills situated on an important ground- or surface water area or landfills of big cities require totally different cover structures from small remote village landfills without groundwater risks. For this reason, in this research, different types of cover structures have been chosen for Finnish landfills.

In the choice of the surface structures the most important factors were the location of the landfill with respect to the ground- or surface water areas, type of waste, the nearness of habitation, the designed enduse and the size of the landfill.

### Structure type 1

Structure type 1 is the highest quality type (Fig. 11a). When the hydraulic barrier is of impermeable material, it can be used when the landfill is situated on the ground- or surface water area. The hydraulic barrier may also need a geomembrane, geosynthetic clay liners, or bentonite mixes when there is a serious threat of contamination of ground- or surface water from the landfill. Daniel (1995), Foster (1995) and Wallace (1993) deal with the use of these materials in the surface structures of landfills. Landfills situated on ground- or surface water areas may also need vertical tightening structures or the changing of direction of running waters by pumping. This structure type is also used when it is intended to build a modern and complex recreation area on the closed landfill of a large city. It can also be used on hazardous waste landfills. The total thickness of the cover systems varies between 2.5–3.0 m and they include a foundation layer, gas control layer, hydraulic barrier drainage layer, vegetation layer and surface layer. The use of filter layers must be decided depending on the used materials. The structure can be also used for planting trees on landfills. The hydraulic conductivity of the hydraulic barrier is the most important factor in preventing infiltration to the wastes. It is dealt with in Chapter 5.

### Structure types 2 and 3

Structure type 2 has the same structure layers as type 1 but they are thinner (Fig. 11b). Structure type 3 has the same structures but there is no gas control layer, because in many landfills a separate system is built with its own wells and pipes for collecting gas (Fig. 11c). These two types fulfill requirements when, for example, the indented enduse of a landfill is for recreational purposes. The total thickness of the cover systems varies between 1.1–1.9 m and they include a foundation layer, gas control layer, hydraulic barrier, drainage layer, vegetation layer and surface layer. Their use on landfills situated on ground- or surface water areas depends on local conditions and the hydraulic conductivity of the hydraulic barrier. It is dealt with in Chapter 5.

### Structure types 4 and 5

Types 4 and 5 represent simple and light cover structures (Fig. 11 d, e). They are used, for exam-

ple, on old landfills where environmental risks are already decreasing. These light structures are also sufficient for small landfills which are situated far from settlements when they are not needed for active purposes, e.g. recreation. The total thickness of the cover systems varies between 0.80–1.0 m and they include a foundation layer, a dense soil layer and a surface layer.

### **2.6.3 The choice of structure type and requirements for the hydraulic barrier**

In the choice of a structure type, a risk assessment should first be made of the environmental consequences of leachate waters from a landfill, in consultation with the environmental authorities, owners and possible other parties (Chapter 6). For example, modelling and earlier research results on environmental consequences of a landfill can be used in a risk assessment. The most important factor is the effect of leachate water on the ground- and surface waters. The results of a risk assessment will determine the requirements for the hydraulic conductivity of the hydraulic barrier and how much infiltration into the wastes can be allowed. When the landfill is situated on a ground- or surface water area and if it can cause contamination, the hydraulic barrier must be constructed of an impervious material. Also, the use of the geomembranes, geosynthetic clay liners, bentonite mixes, vertical tightening structures and changing the direction of running waters by pumping, must be taken into consideration in the design for the protection of ground- or surface water. The choice of the structure type is very much based on its intended enduse. Light structures can be used on landfills which do not have an active enduse. If the landfill is designed for a wide and active enduse, then one must use more superior structures.

### **2.6.4 Factors and remedial measures to be taken into consideration in the use of soil materials in the hydraulic barrier**

After designing and construction of the surface structures, the greatest dangers are the settlements and cracks caused by frost, and decomposition of organic waste which increases the hydraulic

conductivity. Though the landfills are compacted very well, the decomposition of the organic material causes displacements and cracks in the surface structures.

Daniel (1995) has researched this problem. According to him, in USA the materials that have traditionally been considered for the barrier layer within final covers are, in decreasing order of popularity, compacted clay (compacted mineral liner), geomembranes, and geosynthetic clay liners (GCLs). Compacted clay is, according to him, often a poor choice of material. Unless the compacted clay is buried under a very thick layer of protective soil or covered with a geomembrane, it is likely to desiccate and lose its low hydraulic conductivity. Differential settlement of compacted clay from uneven compression of underlying waste produce cracks within the clay. Geomembranes do not suffer as much from these problems, and geosynthetic clay liners are much better able to resist damage from freeze-thaw, desiccation, and differential settlement than compacted clay.

According to Daniel, it is suggested that designers of landfill covers should make more use of geomembranes and GCLs, and less use of compacted clay. However, given the large settlement of waste, particularly in the first few years after the landfill is closed, it seems undesirable to try to construct a final, engineered cover on a fresh, unstable mass of waste. A suggested design approach is: initially to place a temporary, relatively permeable cover on the waste and collect leachate water for several years, treating the landfill as an active bioreactor and after significant biodegradation of the waste has occurred and the waste mass has become relatively stable, to place a final, engineered cover over the waste. By stabilizing the waste prior to placement of a final cover, the probability of the cover performing as designed is maximized.

In the research conducted by Melchior *et al.* (1993), the water balance and the long-term performance of different covers has been monitored on the Georgswerder landfill in Hamburg. The tested liners perform very differently. The compacted soil liners have lost their efficiency due to desiccation and shrinkage, but the flexible membrane liners (HDPE sheet used in combination with compacted soil liners) and an extended capillary barrier perform very well.

### 2.6.5 Construction costs, construction and quality control

Costs of cover systems presented in Chapter 2.6.2 consist of construction and building material costs. Transport distance of materials is in calculations about 10 km. Costs are calculated for 1990. The cheapest cover type costs 210 000 FIM/hectare and the most expensive one costs 2 260 000 FIM/hectare (Table 4).

Cost calculations were made for two alternatives in the following way.

- 1) Most of the cover structures can be built of waste and excess soils free of charge which are transported to the landfill site.
- 2) All soil materials must be bought and transported to the construction site.

Good construction is as important as good design in providing an effective, durable cover system. Construction includes site preparation, planning and scheduling of work, selection and use of proper equipment and site closure. Effective quality control and quality assurance measures are necessary to assure that design specifications are met.

The most important part of surface structures is the hydraulic barrier. In the control of the compaction work, a field laboratory or some laboratory in the vicinity of the landfill can be used. A diary must be kept on quality control. The main issues which must be checked in the compaction work are the quality of the materials used in the compaction, its efficiency and the grain size of the filter material. Loukola (1985a, 1985b, 1994) has studied the general aspects of compaction work of earth structures.

**Table 4.** Construction costs of the cover systems in the year 1991<sup>1)</sup> (Viatek Tapiola Oy 1991). Modified by the author.

Cover type	Waste and excess soil can be used free of charge	All materials must be purchased and transported
	FIM/hectare	FIM/hectare
1	1 440 000	2 260 000
2	1 260 000	1 720 000
3	850 000	1 310 000
4	370 000	640 000
5	210 000	520 000

<sup>1)</sup> Construction costs index has increased 4 % from the year 1991 to the year 1996.

## 3 Earlier models and development of the Landfill Cover Approximation Model (LCAM)

### 3.1 Background

This chapter deals with earlier developed landfill water balance models and the development of a Landfill Cover Approximation Model done in this research. With the developed model it is possible to approximate different factors in the surface structures of landfills to reduce and control the quantity of the infiltration of precipitation into the wastefill in Finnish conditions. There are several water balance models for landfills available in different countries but they are not directly usable for Finnish conditions or they are too complicated for practical purposes, for example, they need a pF-curve of wastes. Fig. 12 shows water movement at a landfill. Fig. 13 shows an example of a hydraulic model as a simulation of the water balance in a landfill.

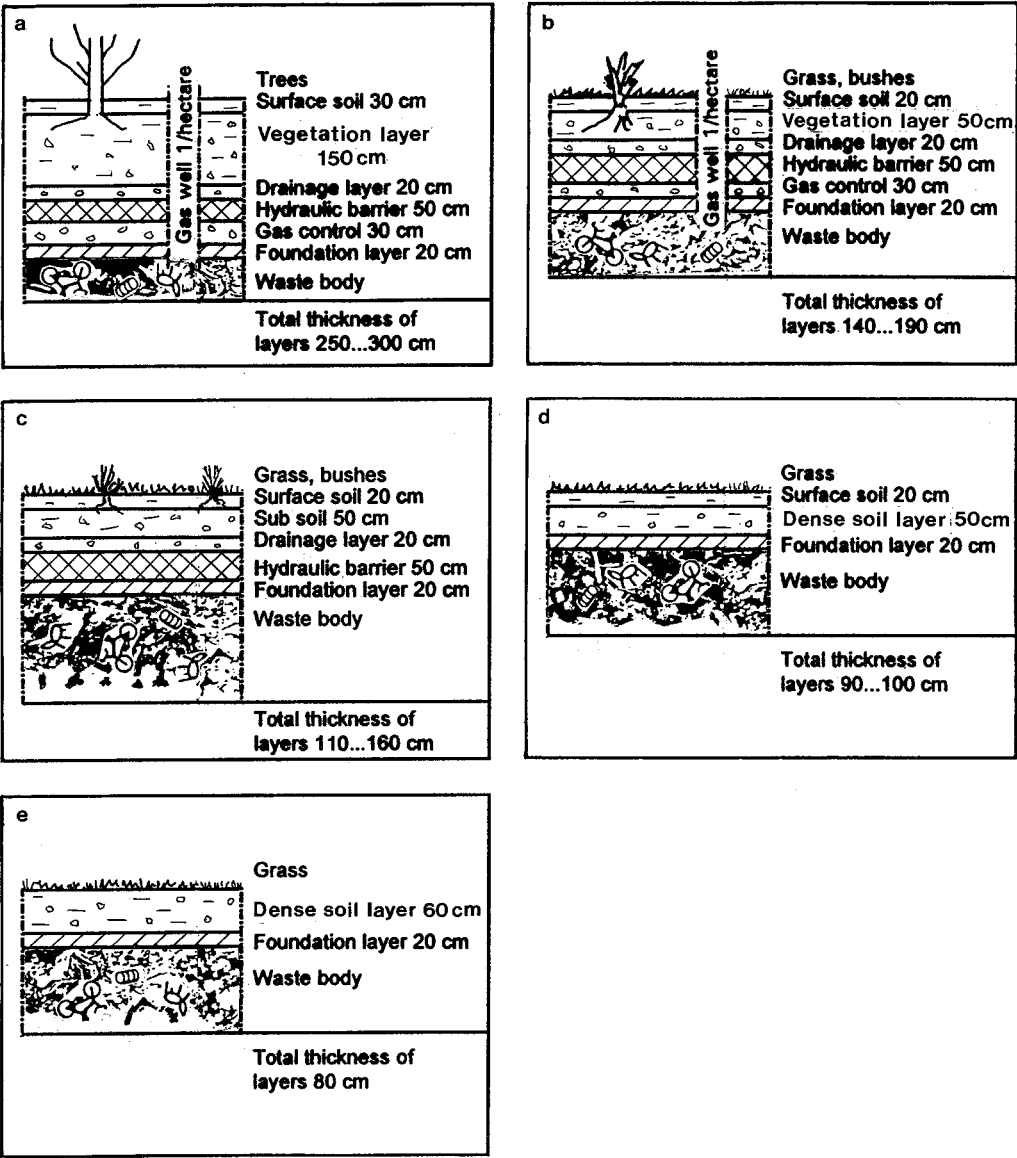
### 3.2 Earlier models

#### 3.2.1 Water Balance Method (WBM)

The water balance method (WBM) was originally developed to serve as a useful engineering tool in conducting environmental assessments of proposed or existing landfill sites, specifically in regards to leachate generation (Fenn *et al.* 1975). The method was intended only as a basic tool for engineers, and certain specific assumptions are needed to tailor the method for a particular location.

The water balance method (WBM) as proposed by Fenn *et al.* (1975) is a manual process solved generally with monthly averaged values. In this model the infiltration fraction of precipitation is the principle contributor to leachate generation from a landfill. Other factors include waste decomposition, initial moisture content of the solid waste and infiltration of groundwater. In the WBM all of these factors are to be assumed negligible for a properly sited and designed landfill, relative to the infiltration fraction of precipitation.

The WBM is based on the relationship between precipitation, evapotranspiration, surface runoff,



**Fig 11.** Surface structure types of landfills. Type 1 (a), type 2 (b), type 3 (c), type 4(d) and type 5 (e). (Viatek Tapiola Oy 1991). Modified by the author. Surface structure types are analysed by LCAM in Chap. 5. According to the results, the hydraulic conductivity of the hydraulic barrier is the most important factor in preventing infiltration of the precipitation to waste.

and soil moisture storage. Evapotranspiration is computed by using the method developed by Thornthwaite method (Thornthwaite and Mather 1957). Surface runoff is computed by using empirical runoff coefficients (rational formula). By applying the coefficients to the mean monthly precipitation, an estimate of "mean monthly surface runoff" can be calculated. Infiltration equals the amount of precipitation minus the surface runoff. In the WBM the maximum amount of soil moisture storage depends on the depth of the rooting zone and the difference between the water content at the field capacity and at the wilting point. The actual computation procedure is a simple bookkeeping method starting from the assumed soil water storage (e.g. field capacity).

Analyses have been performed to compare water balance predictions of leachate flow with actual measurements made in the field. Lu *et al.* (1981) performed comparisons at five landfills using several methods to estimate the components of the water balance. On average, leachate flow estimates were erroneous by a factor of 2. Gee (1981) used two variations of the water balance method to predict leachate flow at the Grows Landfill in Pennsylvania, USA. These predictions were too high by a factor of approximately 2 when compared with the measured leachate flows. However, Kmet (1982) had excellent success using a water balance method to simulate leachate production in Ham's (1980) eight field lysimeters. Leachate flows ranged from 16.6 to 22.1 % of precipitation on an annual basis. Water balance methods predicted an average of 22 % of precipitation. Kmet used the water balance method proposed by Fenn *et al.* (1975) with modification to account for infiltration and runoff from the landfill during winter conditions. Fig. 14 shows the flow chart for the water balance method (WBM). Fig. 15 shows moisture components at a landfill according to Fenn *et al.* (1975).

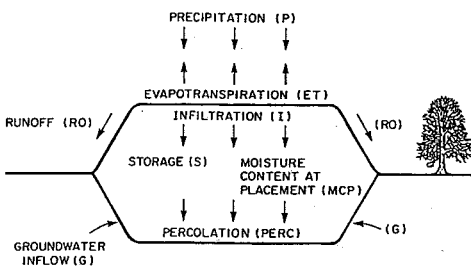


Fig 12. Water movement at a landfill (Farquhar 1989).

### 3.2.2 Improved water balance methods

The original water balance method (WBM) has been improved by calculating the water balance components more accurately. The best-known of these improved models are the HSSWDS (Hydrologic Simulation of Solid Waste Disposal Sites) model and HELP (Hydrologic Evaluation of Landfill Performance) model. Perrier and Gibson (1981) developed the HSSWDS model that was capable of estimating the hydrological situation on a daily basis.

The HELP model was developed to account for the daily changes in the water balance of a landfill (Schroeder *et al.* 1984a, 1984b) and in addition for a shorter computation time. The HELP model is different from the approach proposed by Fenn *et al.* (1975) in two ways. First, the water balance components are treated using more detailed methods. Second, the WBM implicitly assumes that the waste is at field capacity during the whole computation. The HELP model calculates a flow rate through the waste and therefore estimates the time of the first leachate appearance. According to Farquhar (1989), the HELP model is perhaps the best of the available computer models.

The HELP model computes the water balance for landfills by performing a daily analysis using a so-called quasi two-dimensional approach (one-dimensional both in vertical and horizontal direction). The hydrologic components included are precipitation in any form, surface storage, interception, surface evaporation, runoff, snow melt, infiltration, vegetation, rooting depth, plant transpiration, soil evaporation, soil moisture storage, soil moisture potential, unsaturated flow, and vertical and lateral saturated flow. The Soil Conservation Service (SCS) curve number technique is used to partition incoming rainfall or snow melt between surface runoff and infiltration. Evapotranspiration in the HELP model is computed using a modified Penman method as described by Ritchie (1972). Soil water is routed vertically through the soil by a simultaneous solution of Darcy's law and the equation of continuity. The unsaturated hydraulic conductivity is assumed to be zero when soil moisture is at or below field capacity and is equal to the saturated hydraulic conductivity when the soil is saturated. Lateral flow above the liner is modelled based on a linearization of the steady-state Boussinesq equation performed by Skaggs (1982). The HELP model includes an optional de-

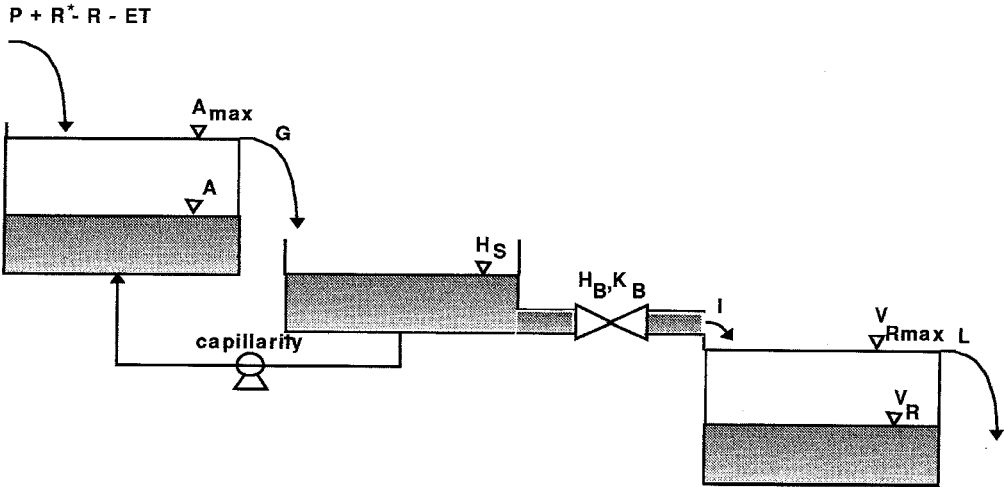


Fig. 13. An example of a hydraulic model as a simulation of the water balance in a landfill.  $P$ : precipitation;  $ET$ : actual evapotranspiration;  $R^*$ : runoff from external areas;  $R$ : runoff;  $A$ : water content of soil cover;  $U$ : field capacity of soil cover;  $G$ : water infiltration under soil cover;  $K_B$ : Darcy's hydraulic transmissivity ( $L T^{-1}$ );  $L$ : leachate;  $H_B$ : thickness of the low-permeability barrier;  $H_s$ : saturated layer;  $V_R$ : water content of wastes;  $V_{Rmax}$ : field capacity of wastes (Canziani and Cossu 1989).

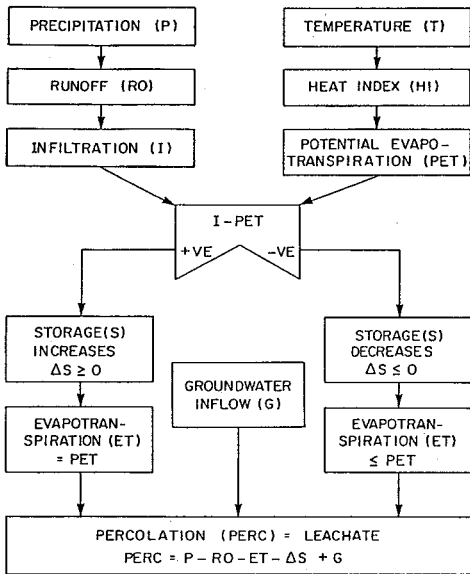


Fig. 14. Flow chart for the water balance method (Farquhar 1989).

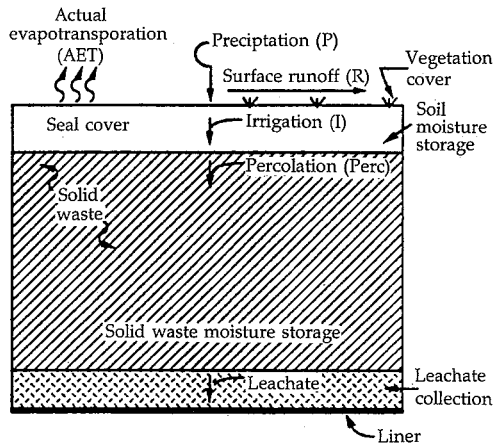


Fig. 15. Moisture components at a landfill (Fenn *et al.* 1975).

fault data base that describes the climate for 102 cities (precipitation, temperature, solar radiation, and growing season); seven types of vegetation cover; soil characteristics for 21 soil types; and the runoff curve numbers for default soil and vegetation types (Peyton and Schroeder 1989).

Peyton and Schroeder (1989) have performed long-term simulations using the HELP model. They found that model predictions are generally bracketed by field measurements. Good agreement between the predictions and measurements is obtained by calibrating the hydraulic conductivity of the cover materials whilst staying within the range of hydraulic conductivity values reported in the literature for these materials. The results indicated that the HELP model can be a very useful tool for designing and evaluating landfills. However, according to Peyton and Schroeder (1989), the overall data base of long-term waterbudget measurements is poorly organized and too small to continually advance the state of understanding landfill leachate generation and migration. More extensive monitoring activities are required to fill this gap.

An attempt to apply the HELP model for estimating the quantity of leachate to be generated has been done also by Kastury *et al.* (1985). Table 5 shows components of the WBM and comparison with the HELP model.

Canziani and Cossu (1989) have developed a model based on similar assumptions as the HSSWDS model but with monthly intervals to evaluate the possibility of utilizing the model as a tool in the design of landfills. The model can be applied to landfills in operation and to completed landfills with a final cover and a low permeability layer under the final cover. The meteorological data needed by the model are air temperature, precipitation and solar radiation. The morphological data of the soil cover include thickness, soil type, slope and information about grassed surfaces. The characteristics of wastes include layer thickness, insitu density and water retention capacity of the waste.

According to the sensitivity analysis the parameters which mostly influence the model are, in order of importance, the hydraulic conductivity of the capping layer, the method for calculating evapotranspiration, the field capacity of the cover material and the water retention capacity of the waste.

According to the application of the model for estimating leachate production, two observations can be made. First, the model can estimate with

sufficient approximation monthly variations. Second, a good fit between the observed and estimated values depends above all on the climatic parameters and on the waste parameters which should be strictly measured on site. Fig. 16 shows a schematic diagram of the general hydrological balance in a completed landfill according to Canziani and Cossu (1989). Fig. 17 shows the schematic flow sheet of the leachate hydrological balance algorithm for Canziani and Cossu's model.

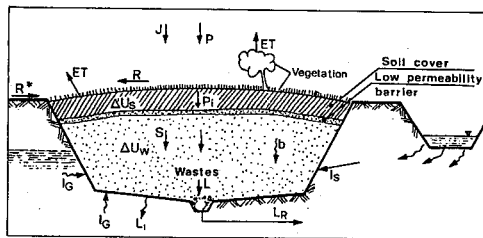


Fig. 16. Schematic diagram of the general hydrological balance in a completed landfill with leachate drainage system.  $P$ : precipitation;  $J$ : irrigation or leachate recirculation;  $R$ : surface runoff;  $R'$ : runoff from external areas;  $ET$ : actual evapotranspiration;  $P_t = P + J + R' - R - ET \pm \Delta U_s$ ;  $U_s$ : water content in soil;  $U_w$ : water content in wastes;  $S$ : water added by sludge disposal;  $b$ : water production (if  $> 0$ ) or consumption (if  $< 0$ ) caused by the biological degradation of organic matter;  $I_s$ ,  $I_g$ : water from natural aquifers;  $P_t = P_i$ ;  $S + I_s + I_g$ ;  $L = P_t \pm \Delta U_w + b$ : total leachate production;  $L_i$  = infiltration into aquifers;  $L_d$ : leachate collected by drains (Canziani and Cossu 1989).

### 3.2.3 LANCEL model

The development of the LANCEL (LANDfill CELLular liquids model) dynamic simulation model was motivated by the need to describe the local liquid hydrology at a landfill site (Rice *et al.* 1985). The main aim of the LANCEL model was to evaluate how the present system performs and to examine the alternative liquid management schemes both now and in the future. The LANCEL model is a planning-level tool. The results of the model simulations are applicable to decisions on overall leachate management strategies.

LANCEL differs from the HELP model in two main aspects. Firstly, the landfill area is divided into cells or nodes making the model truly two-dimensional as compared to the quasi two-dimensional structure of the HELP model. The cell geometry of the LANCEL model is similar to that used by finite element methods. Secondly, the unsaturated soil is divided into layers within each cell.



**Table 5.** Components of the WBM and comparison with the HELP model (Farquhar 1989).

WBM	HELP model
1. Potential evapotranspiration (PET) – the potential amount of moisture that can evaporate from soil and (or) waste and transpire from vegetative cover depending upon temperature (T) and solar radiation Thornthwaite method (Thornthwaite and Mather 1957)  Data input Temperature: Monthly Heat index: Monthly	Penman method (Penman 1948)  Daily Monthly
2. Precipitation (P) – the precipitation in all forms falling on the site Monthly averages	Daily averages (choice available)
3. Runoff (RO) – that portion of precipitation which runs off the site and does not infiltrate Thornthwaite and Mather (1957) Fenn et al. (1975) $RO = C_{RO}P$ ( $C_{RO}$ is a runoff coefficient) Data input Vegetation Slope Soil types Surface treatment	U.S. Department of Agriculture (1975)  Same as WBM
4. Infiltration (I) – that portion of precipitation which infiltrates the site $I = P - RO$	Same as WBM
5. Soil moisture storage (S) – the amount of infiltration which is retained in the soil and (or) waste up to field capacity and thus does not percolate as leachate (S <sub>MAX</sub> is the maximum S for soil or refuse)  Thornthwaite and Mather (1957) Data input Soil type Depth Field capacity Moisture content (MC) Wilting point (WP) $\Delta S$ (change in S) = + ve when $1 > 0$ and $MC < S_{MAX}$ = - ve when $(1 - PET) < 0$ and $MC > WP$	Same as WBM
6. Actual evapotranspiration (ET) – the actual amount of evapotranspiration ( $ET \leq PET$ ) which occurs; depends on the soil types and depths, vegetation type, root depth, MC  $ET \leq PET - (1 - PET) - \Delta S$	
7. Percolation (PERC) – the amount of liquid which reaches the base of the landfill to become leachate $PERC = P - RO - ET - \Delta S + G$	

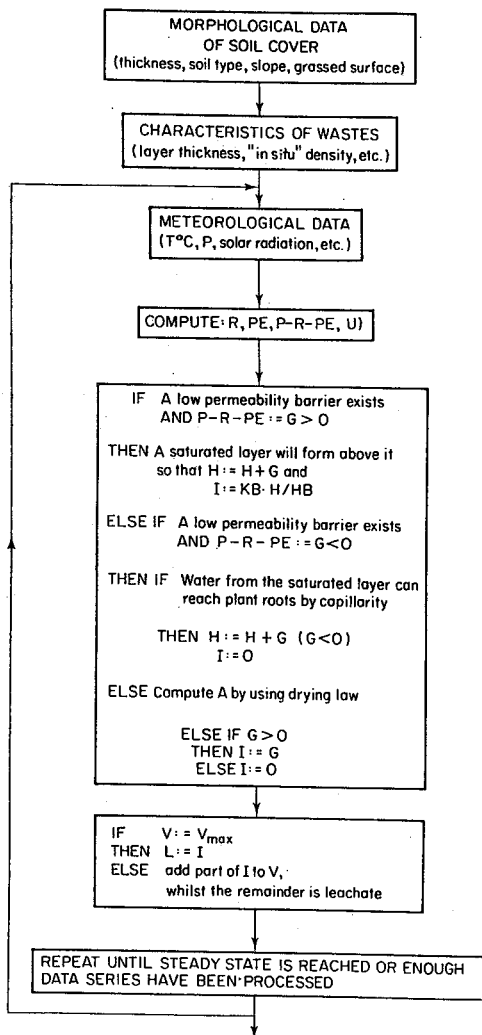


Fig. 17. Schematic flow sheet of leachate hydrological balance algorithm. Symbols are as in Fig. 13. (Canziani and Cossu 1989).

The unsaturated subsystem is modelled using a cascade of non-linear reservoirs and the outflow from the final reservoir serves as an input to the saturated subsystem. In the saturated subsystem, liquids can follow many different flow paths, i.e. they can flow laterally to adjacent cells, flow to adjacent curtain drains, or flow out through the base of the landfill. The data requirements of the LANCEL are greater than those of the HELP model, mainly due to the two-dimensional cell system.

Rice *et al.* (1985) have tested the LANCEL model against data collected at the Omega Hills

North Landfill, USA. The LANCEL model simulation results provided important information for the response to various leachate management alternatives. Moreover, the model provided insight into moisture movement processes which have general applicability to many landfill problems. In addition, the LANCEL simulations indicated that the most efficient long-term leachate management alternative is the construction of a low percolation landfill cover. Fig. 18 shows schematic diagram illustrating the LANCEL model.

### 3.2.4 Numerical solution of flow through landfills

The previously described models have not studied adequately the mechanisms of moisture transport through the waste. Korfiatis *et al.* (1984), and Demetracopoulos *et al.* (1984, 1986) have published a model that uses a numerical solution of the equation of continuity and motion (Darcy's Law). The solution of the equation is obtained by a fully implicit finite difference scheme. Both saturated and unsaturated conditions are considered. The model can be used to evaluate leachate quantities discharged from existing active or inactive landfills.

The basic difference between the HELP or LANCEL model and the numerical solution used by Korfiatis *et al.* (1984) is the need to have the soil water retention curve (soil moisture content versus soil water potential) and hydraulic conductivity of soil and diffusivity functions as the input data. For landfill areas, these types of functions are very difficult to obtain due to the inhomogeneity of the landfill waste. According to Demetracopoulos *et al.* (1986), there are two basic reasons as to why the numerical solution of flow through the landfill is desired. First, moisture fluxes are needed at discrete points through the landfill, in order to describe the advective term of mass transport (quality) models. Second, the time history of leachate discharge is required for real time modelling and subsequent hydraulic design of the leachate bottom collection system.

According to a sensitivity analysis carried out by Demetracopoulos *et al.* (1986), the model is sensitive to changes in the physical properties of the porous medium. For saturated surface conditions, the grid size and time step influence the solution. Fig. 19 shows a simplified model flow chart according to Korfiatis *et al.* (1984).

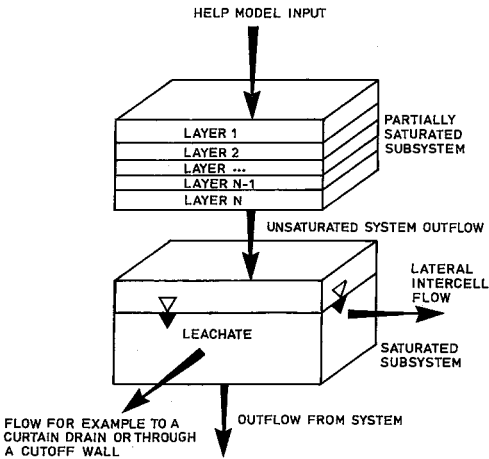


Fig. 18. Schematic diagram illustrating the LANCEL model (Rice *et al.* 1985).

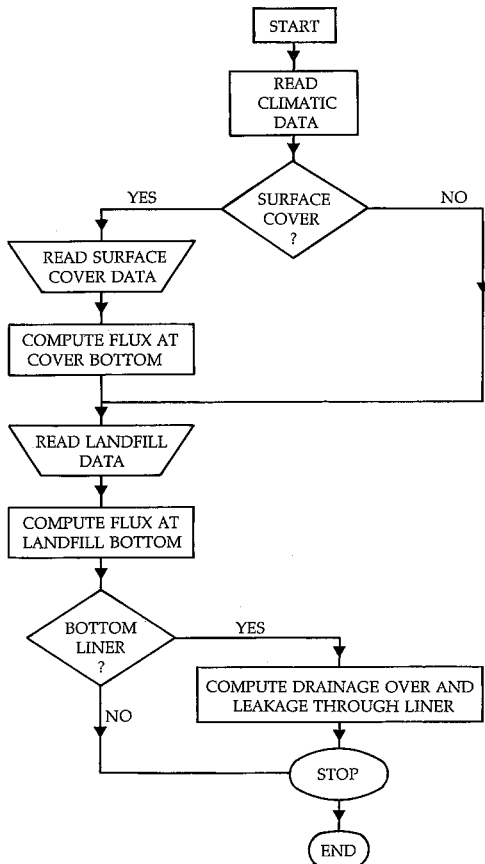


Fig. 19. Simplified flow chart of the model of Korfiatis *et al.* (1984).

### 3.2.5 Use of a groundwater model in the landfill water balance

The previously described approaches – WBM, HSSWDS, HELP, LANCE and the numerical solution of moisture movement – are based on the idea of solving the water fluxes in a one-dimensional vertical system. Karlqvist (1987) has chosen a completely different approach, i.e. a groundwater model to illustrate groundwater potential at a landfill area. A technique called the Analytic Element Method uses analytical functions for solving the potential formulation of the differential equations for groundwater flow. The modelling of the landfill systems is performed by superimposition of functions called analytic elements. Each of these functions represents a particular feature of the landfill system to be modelled. Analytic functions have been developed for wells, lakes, rivers with leaky bottoms, canals, cracks and impermeable boundaries. Even inhomogeneity in the landfill can be dealt with in the model.

The input data needed by the model include landfill parameters (hydraulic conductivity), depth of the solid waste, groundwater recharge, and location of canals. The canals are assumed to be in direct contact with the groundwater system implying that they act as hydraulic boundaries.

The model is calibrated by adjusting the infiltration to the landfill so that the calculated groundwater heads, within the area of interest, will be in accordance with the general picture of the measured groundwater levels. According to Karlqvist (1987), brief model calculations showed that drainage features such as streams, ditches, lakes, peat bogs and fracture zones have a pronounced effect on the groundwater level.

The usefulness of the approach utilized by Karlqvist (1987) is limited by two main factors:

- the model needs infiltration into the waste as input data (recharge term) but on the other hand it should be computed by the model
- groundwater level data used in the calibration are not always available from landfill sites.

### 3.2.6 Stochastic approach to precipitation

The previously described models are deterministic and are not able to investigate the effect of stochastic precipitation conditions on moisture infil-

tration quantities. Baetz and Byer (1989) described a stochastic simulation model to represent the construction of a landfill and associated moisture control options. Modelling results show that stochastic, rather than average precipitation inputs should be considered. The model developed by Baetz and Byer differs from the previous approach in such a way that infiltration is modelled using the Green and Ampt theory (1911) and snowmelt is included in the model. Snow removal was shown to be an operational variable that potentially has a significant impact on the moisture content at a landfill site. This has been previously shown by Ettala (1988a).

Summary of the main features of the models mentioned in Chapters 3.2.1–3.2.6 and the comparison of LCAM to them are presented in Chapter 3.3.5 and in Table 6.

### 3.3 Structure of LCAM

#### 3.3.1 Two presuppositions of LCAM

The first presupposition of LCAM is that the spreading of water in wastes is not modelled at all, but the result given by the model is the quantity of the water that infiltrates through, hydraulic barrier into the wastes. According to Ettala (1987a), the infiltration into landfills is mostly over  $1 \text{ mm min}^{-1}$ . The results mean that after permeating through the hydraulic barrier the spreading of water in wastes is quick compared to the heaviness of precipitation and the snow melt.

Leaving wastes from the model is also supported by measurements of hydraulic conductivities done by Ettala (1987a). According to his results, variations of hydraulic conductivities are great in different landfills and also in different places of the same landfill. When wastes are not in the model, there is also no need to know the pF-curve of wastes, as for example, in numerical models presented by Korfiatis *et al.* (1984) and Demitracopoulos *et al.* (1984, 1986). For landfills pF-curve is difficult to obtain due to the inhomogeneity of the landfill waste.

The other presupposition of the model is that there must be a part of the model which describes vegetation and its development, with which interception is calculated. In field research the interception of willow plantations has been about 30 % of the sum of precipitation and sprinkler irrigation

(Ettala 1987b). For this reason interception must be in the model.

#### 3.3.2 Main components of LCAM

##### *Precipitation*

Annual precipitation can be chosen from six different regions: Helsinki, Jokioinen, Jyväskylä, Kuopio, Sodankylä and Utsjoki. Hydrological data for years 1973–1988 from each location are in LCAM, and the user of the model can choose the number of years for the simulation. By using a long time period in the simulation, it is possible to calculate the average quantity of leachate waters for several years.

##### *Interception*

Part of the precipitation is intercepted by the leaves of trees and this water evaporates quickly after rain. According to Ettala (1987b, 1988a), interception from willows can be about 30 % of the total precipitation.

##### *Water balance of the surface layer*

The precipitation, which comes through vegetation increases the soil water storage of the surface layer. The water quantity of this storage is reduced by evaporation, surface layer runoff and infiltration into the wastes. In some cases, the storage ability of the surface layer becomes exhausted and then excess water flows away as surface runoff. The surface runoff is calculated from the water content of the soil, slope and length of the slope and from the thickness and hydraulic conductivity of the surface layer.

It is possible to build the drainage layer between the surface layer and the hydraulic barrier, which has very good hydraulic conductivity (minimum  $10^{-4} \text{ m s}^{-1}$ ). The drainage layer can lead away part of the water and infiltration into the wastes is then reduced.

##### *Potential and actual evapotranspiration*

Potential evapotranspiration  $E_{pot}$  is calculated in LCAM from the daily total radiation and average temperatures. Values of these variables for over

16 years are stored in LCAM. The actual evapotranspiration from the surface layer depends on the usable water storage  $W$ . The maximum water content of the surface layer is obtained by multiplying the layer thickness with the efficient porous volume, which means the difference between water content of the saturated water content and the withering point. The thicker the surface layer is, the greater water storage the vegetation has available. The actual evapotranspiration is less than the potential evapotranspiration when the water storage is smaller than the limit value  $W_{\text{evap}}$  (Fig. 20), given as a parameter. In dry years vegetation withers easily, which is taken into consideration in LCAM, so that the user estimates the condition of the vegetation from practical experience from 1–10. In the calculation formulas the poor condition of vegetation has an effect in reducing the area of the leaves which then reduces the interception of rainfall by the leaves.

#### Estimation of infiltration

In LCAM it is supposed that the water potential in the soil is always in hydraulic balance, or in practice, the balance is attained at once after rainfall has ceased. The accuracy of this most important simplification of the model is presented in Chapter 3.4. The infiltration through the hydraulic barrier can take place when the water potential in the bottom of the surface layer is greater than the water potential in the lower surface of the hydraulic barrier (given as a parameter). Other parameters which affect the quantity of infiltration are the hydraulic conductivity and the thickness of the hydraulic barrier.

Fig. 21 shows the main components of LCAM. Fig. 22 shows a schematic flow chart of LCAM.

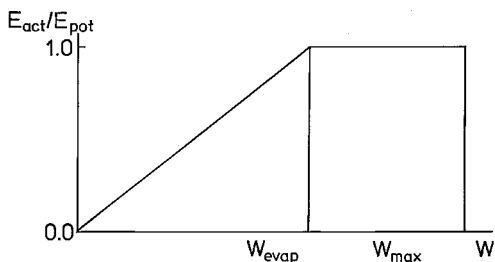


Fig. 20. Relation between actual and potential evapotranspiration as a function of quantity of water ( $W$ ) in the surface layer of soil.

### 3.3.3 Equations of LCAM

The equations of LCAM are given in the computational sequence.

At the beginning of the computation, an initial value for the soil water storage of the surface layer needs to be given:

$$W_{\text{max}} = \Theta_p \cdot D_p \quad (3)$$

$$W = R_{W,\text{start}} \cdot W_{\text{max}} \quad (4)$$

where

$W_{\text{max}}$  = maximum value for water content in the surface layer (mm)

$\Theta_p$  = porosity ( $\text{m}^3 \text{m}^{-3}$ )

$D_p$  = thickness of the surface layer (mm)

$W$  = water content in the surface layer (mm)

$R_{W,\text{start}}$  = initial value for relative water content (0.5...0.7)

The time step of the computation is one day. The computation starts on January 1st and if there is snowcover in the landfill area, the model needs the snow water equivalent as an initial value. The computation of the snowmelt is based on the degree-day concept as follows:

$$M = k_M \cdot (T_A - T_{\text{base}}) \quad ; \quad T_A \geq T_{\text{base}} \quad (5)$$

$$M = 0 \quad \text{if} \quad T_A < T_{\text{base}}$$

where

$M$  = snowmelt ( $\text{mm d}^{-1}$ )

$k_M$  = degree-day factor for snowmelt ( $\text{mm d}^{-1} \text{ } ^\circ\text{C}^{-1}$ )

$T_A$  = daily average air temperature ( $^\circ\text{C}$ )

$T_{\text{base}}$  = base temperature for snowmelt ( $^\circ\text{C}$ ) (usually about  $0 \text{ } ^\circ\text{C}$ )

The next step is to calculate the relative value of soil water storage  $R_W$ :

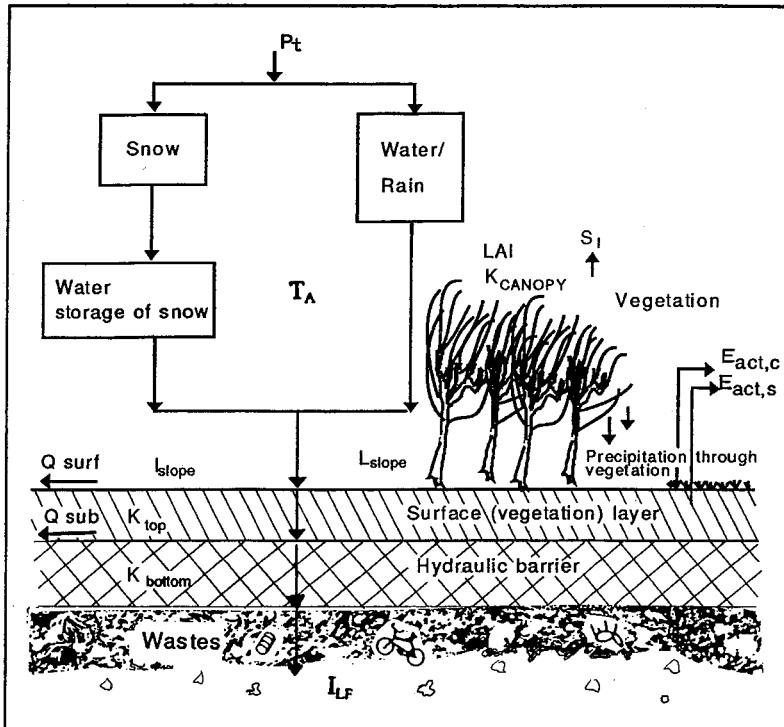
$$R_W = W/W_{\text{max}} \quad (6)$$

where

$R_W$  = relative water content in the surface layer ( $W/W_{\text{max}}$ )

$W$  = water content in the surface layer (mm)

$W_{\text{max}}$  = maximum value for water content in the surface layer (mm)



### Legend

$P_t$ = Precipitation	$I_{slope}$ = Average slope of the landfill
$Q_{sub}$ = Subsurface runoff	$L_{slope}$ = Average length of the slope
$Q_{surf}$ = Surface runoff	$K_{CANOPY}$ = Quality of the canopy
$S_i$ = Interception	$LAI$ = Leaf area index
$I_{LF}$ = Infiltration to waste	$K_{top}$ = Hydraulic conductivity of the surface layer
$E_{act,c}$ = Actual evaporation from the canopy	$K_{bottom}$ = Hydraulic conductivity of the hydraulic barrier
$E_{act,s}$ = Actual evaporation from bare soil	$T_A$ = Daily average air temperature

Fig. 21. Main components of LCAM.

According to the model, infiltration  $I_{LF}$  into the landfill is:

$$I_{LF} = -K_b (H_L - H_p)/D_b \quad (7)$$

where

- $I_{LF}$  = infiltration into landfill (mm d<sup>-1</sup>)  
 $K_b$  = hydraulic conductivity of the hydraulic barrier layer (m s<sup>-1</sup>)  
 $D_b$  = thickness of the hydraulic barrier (mm)

$H_L$  = hydraulic height in the bottom of the hydraulic barrier (mm)

$H_p$  = hydraulic height in the surface the of hydraulic barrier (mm)

Subsurface runoff is assumed to exist when  $R_w$  is greater than  $R_{sub}$ :

$$Q_{sub} = K_{top} \cdot I_{slope} \cdot (R_w - R_{sub}) / (1.0 - R_{sub}) ;$$

$$R_w \geq R_{sub} \quad (8)$$

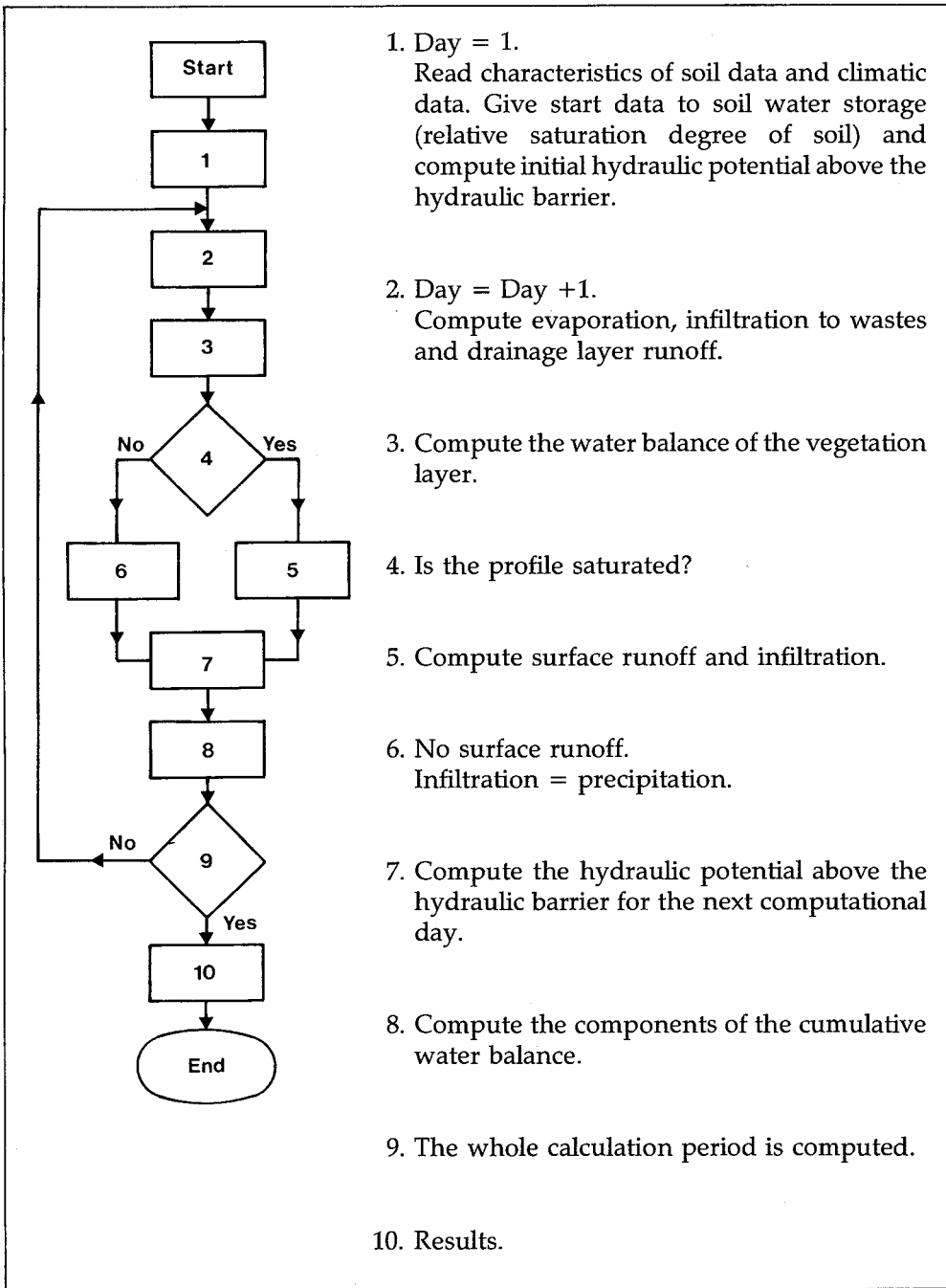


Fig. 22. Schematic flow chart of LCAM.

Subsurface runoff is assumed to exist when  $R_W$  is greater than  $R_{sub}$ :

$$Q_{sub} = K_{top} \cdot I_{slope} \cdot (R_W - R_{sub}) / (1.0 - R_{sub});$$

$$R_W \geq R_{sub} \quad (8)$$

$$Q_{sub} = 0 \quad \text{if} \quad R_W < R_{sub}$$

where

- $Q_{sub}$  = subsurface runoff (mm d<sup>-1</sup>)
- $K_{top}$  = hydraulic conductivity of the surface layer (m s<sup>-1</sup>)
- $I_{slope}$  = average slope of the landfill (m m<sup>-1</sup>)
- $R_W$  = relative water content in the surface layer ( $W/W_{MAX}$ )
- $R_{sub}$  = subsurface runoff can be formed if relative water content in the surface layer is greater than this value (0.4..0.7)

Drainage layer runoff is calculated:

$$Q_D = K_D I_{slope} D_D / L_{slope} \quad (9)$$

where

- $Q_D$  = drainage layer runoff (mm d<sup>-1</sup>)
- $K_D$  = hydraulic conductivity of the drainage layer (m d<sup>-1</sup>)
- $I_{slope}$  = average slope of landfill (m m<sup>-1</sup>)
- $D_D$  = thickness of the drainage layer (mm)
- $L_{slope}$  = average length of slope (m)

Actual evapotranspiration is calculated from the potential evapotranspiration and relative soil water content in the surface layer:

$$\alpha_E = 1.0 \quad ; \quad R_W \geq R_{evapo} \quad (10)$$

$$\alpha_E = (R_W / R_{evapo}) \quad ; \quad R_W < R_{evapo}$$

where

- $\alpha_E$  = ratio of actual and potential evapotranspiration
- $R_W$  = relative water content in the surface layer ( $W/W_{max}$ )
- $R_{evapo}$  = relative water content, below which too dry soils start to limit actual evaporation (0.6..0.8)

The leaf area index of the canopy, LAI, is a function of the effective temperature sum, ETS, which is computed as follows:

$$ETS_i = ETS_{i-1} + (T_A - 5.0) \quad ; \quad T_A > + 5^\circ C \quad (11)$$

$$ETS_i = ETS_{i-1} \quad ; \quad T_A \leq + 5^\circ C$$

where

- $ETS_i$  and  $ETS_{i-1}$  = effective temperature sum (dd) for days  $i$  and  $i-1$
- $T_A$  = daily average air temperature (°C)

In the optimal conditions the canopy is not suffering from a water or nutrient shortage and LAI is given as a prescribed function of ETS.

ETS is calculated throughout the growing season and LAI in optimal conditions can be calculated for each day of the year. The actual LAI used in the computations is taken into account by a subjective parameter  $K_{CANOPY}$  indicating the quality of the canopy using a scale 0..10.

$$LAI = (K_{CANOPY} / 10) \cdot LAI_{opt} \quad (12)$$

where

- LAI = leaf area index (m<sup>2</sup> m<sup>-2</sup>)
- $LAI_{opt}$  = leaf area index in optimal conditions (m<sup>2</sup> m<sup>-2</sup>) (about 5)
- $K_{CANOPY}$  = quality of the canopy (0..10)

If there is no canopy in the landfill area, LAI = 0. The next step is to calculate actual and potential evaporation from bare soil and from vegetation.

$$E_{pot,s} = e^{(K_{ext} \cdot LAI)} \cdot R_{E,s} \cdot E_{pot} \quad (13)$$

$$E_{act,s} = \alpha_E \cdot E_{pot,s} \quad (14)$$

$$E_{pot,c} = [1.0 - e^{(K_{ext} \cdot LAI)}] \cdot R_{E,c} \cdot E_{pot} \quad (15)$$

$$E_{act,c} = \alpha_E \cdot E_{pot,c} \quad (16)$$

where

- $E_{pot,s}$  = potential evaporation from bare soil (mm d<sup>-1</sup>)
- $K_{ext}$  = radiation extinction coefficient (0.5..0.7)
- $R_{E,s}$  = evaporation factor for bare soil (0.4..0.6)
- $E_{pot}$  = potential evapotranspiration calculated from meteorological variables (mm d<sup>-1</sup>)
- $R_{E,c}$  = evaporation factor for vegetation (usually 1.0)
- $E_{act,s}$  = actual evaporation from bare soil (mm d<sup>-1</sup>)
- $\alpha_E$  = ratio of actual and potential evapotranspiration



$E_{act,c}$  = actual evaporation from the canopy  
(mm d<sup>-1</sup>)

$E_{pot,c}$  = potential evaporation from the canopy  
(mm d<sup>-1</sup>)

The parameters  $R_{E,s}$  and  $R_{E,c}$  in Eqs. (13) and (15) take into account the fact that evaporation from bare soil is usually 40–60 % lower than evaporation from vegetation.

Interception is dependent on an estimated leaf area index and rainfall intensity. The assumption included in the model is that interception is linearly dependent on LAI:

$$S_{I,max} = C_I \cdot LAI \quad (17)$$

$S_{I,max}$  = maximum value for interception storage  
(mm)

$C_I$  = parameter indicating the maximum value of interception storage (mm) (0.2..0.5)

If rainfall is less than  $S_{I,max}$ , all precipitation is evaporated from leaf surfaces. If rainfall is greater than  $S_{I,max}$ , the surplus increases the water content of the surface layer. Potential evapotranspiration is reduced according to the estimated interception.

The soil water content of the surface layer can now be calculated as:

$$W_i = W_{i-1} + P_t - E_{act,s} - E_{act,c} - Q_{sub} \cdot (D_p) / (1000 L_{slope}) - I_{LF} \quad (18)$$

where

$P_t$  = precipitation (mm d<sup>-1</sup>)

$W_{i-1}, W_i$  = water content in the surface layer at the beginning and at the end of the day i (mm)

$E_{act,c}$  = actual evaporation from the canopy  
(mm d<sup>-1</sup>)

$E_{act,s}$  = actual evaporation from bare soil  
(mm d<sup>-1</sup>)

$Q_{sub}$  = subsurface runoff (mm d<sup>-1</sup>)

$L_{slope}$  = average length of the slope (m)

Surface runoff can be formed when the surface layer is saturated, i.e. the water content, as calculated by Eq. (18), exceeds its maximum value  $W_{max}$  and the surplus increases the depression storage of the landfill surface.

$$S_{p,i} = S_{p,i-1} + (W_i - W_{max}) \quad ; \quad W_i > W_{max} \quad (19)$$

$$S_{p,i} = 0 \quad \text{if} \quad W_i \leq W_{max}$$

$$Q_{surf} = S_{p,i} - S_{p,max} \quad ; \quad S_{p,i} > S_{p,max} \quad (20)$$

$$Q_{surf} = 0 \quad \text{if} \quad S_{p,i} \leq S_{p,max}$$

where

$Q_{surf}$  = surface runoff (mm d<sup>-1</sup>)

$S_{p,i-1}, S_{p,i}$  = value of the depression storage for days i-1 and i

$S_{I,max}$  = maximum value for interception storage (mm)

$S_{p,max}$  = maximum value for the depression storage (mm)

$W_i$  = water content in the surface layer at the beginning and at the end of the day i (mm)

$W_{max}$  = maximum value for water content in the surface layer (mm)

If  $W_i$  as calculated by Eq.(18), is greater than  $W_{max}$  then a substitution  $W_i = W_{max}$  is carried out. Correspondingly, the calculated value of the depression storage cannot exceed its maximum value  $S_{p,max}$ .

At the end of each computational day, the cumulative sums of the following water balance components are increased:

- precipitation
- interception
- actual evapotranspiration (vegetation and bare soil)
- potential evapotranspiration (vegetation and bare soil)
- subsurface runoff or surface layer runoff
- surface runoff
- infiltration into the landfill

### 3.3.4 The variables of LCAM

The variables required in LCAM are classified into three categories:

- the physical characteristics of the soil layers
- the required parameters in calculating the infiltration, surface runoff and surface layer runoff
- empirical variables which affect the quality and condition of the plant stand.

Required variables for LCAM are shown in App. 3.

### 3.3.5 The comparison of LCAM to other models

None of the landfill water balance models mentioned in Chapter 3.2 were directly usable for the planning and approximation of landfill surface structures in Finnish conditions. The HELP, HSSWDS, LANCEL, Karlqvist (1987)'s model and Canziani and Cossu (1989) models suppose among other things that hydraulic conductivity of wastes is known. However, it is not in the structure of LCAM developed in this work. Only the HELP and Canziani and Cossu (1989) model have possibilities to consider the development of different vegetation types and their effects on the quantity of infiltration. The partial model con-

cerning accumulation and melting of snow are only in the HELP-model and in the model presented by Baetz and Byer (1989). Table 6 shows, as a summary, the comparison of the differences between the earlier developed models and the Landfill Cover Approximation Model (LCAM).

LCAM was developed by Saarela and Karvonen (Chap. 3). Saarela was responsible for the total development, the testings and the simulations of the model and Karvonen was responsible for the mathematical part of the modelling. Ettala has earlier made wide and thorough landfill studies in Finland. His research results were used in the choice of the components of LCAM (Ettala 1986, 1987b, 1988a, 1988b).

**Table 6.** The comparison of the differences between the earlier developed models and the Landfill Cover Structure Model (LCAM) developed in this research.

Model	The model needs the hydraulic qualities of wastes		The model takes into consideration the effects of the vegetation on the quantity of leachate waters by the partial model		Accumulation and melting of snow is calculated by the partial model	
	yes	no	yes	no	yes	no
LCAM (Landfill Cover Approximation Model)		x	x		x	
WBM	x			x		x
HELP	x		x		x	
HSSWD	x			x		x
LANCEL	x			x		x
Karlqvist (1987)	x			x		x
Korfiatis <i>et al.</i> (1984)	x			x		x
Canziani and Cossu (1989)	x		x			x
Baetz and Byer (1989)	x			x	x	

### 3.4 Effects of primary assumptions on accuracy of numerical analysis in LCAM

#### 3.4.1 Presuppositions

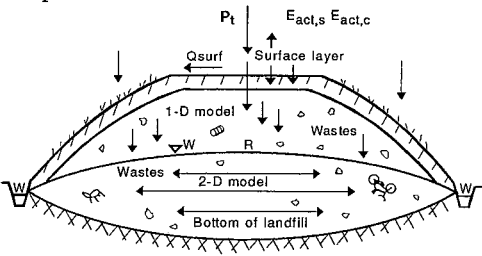
From the hydrological point of view, LCAM has two fundamental presuppositions, which are:

- after rainfall the surface layer is at once in a hydraulic balance state
- wastes are defined outside the model or the delay of water is considered with the simple linear basin instead of a two-dimensional groundwater model.

The effect of these two suppositions on the accuracy of the results is considered in this chapter by comparing the results of LCAM to the results of the complicated, three-dimensional model.

#### 3.4.2 The quasi 3-D water balance model of a landfill

This chapter combines a one-dimensional model, which describes infiltration and the vertical movement of water, with a two-dimensional groundwater model, which describes the horizontal movement of water. The result is the quasi three-dimensional model (Fig. 23) and the results given by it are compared to the results of LCAM described in Chap. 3.3.



**Fig. 23.** Schematic figure of the use of the 1-D model in the calculation of vertical movement of water and the 2-D model in the calculation of horizontal movement of water in the wastefill. These two models are connected with the boundary conditions (the recharge term  $R$ ) e.g. the depth of the groundwater level calculated by the 2-D model is the lower boundary condition of the 1-D model. The result is a so called quasi 3-D model.

#### 3.4.3 Numerical analysis of infiltration

Several methods have been developed during the last decades for the numerical analysis of infiltration to the soil. Hydraulic conductivity, moisture

content of the surface layer and the heaviness of the precipitation affect infiltration most. Physically, the most justified way to calculate infiltration is to use the so-called Richards' equation, which describes the flow of water in unsaturated-saturated soil systems. The Richards' equation has to be solved numerically with difference and element methods, (Nimah and Hanjks 1973; Feddes *et al.* 1978; Jensen 1983; Pingoud 1982, 1983; Vakkilainen 1982; Karvonen 1988).

$$c(h) \frac{\partial h}{\partial t} = \frac{\partial}{\partial z} [K(h) \left( \frac{\partial h}{\partial z} - 1 \right)] - S(h) \quad (21)$$

where

$h$  = soil water potential (m)

$K(h)$  = hydraulic conductivity ( $\text{m d}^{-1}$ )

$z$  = position of the vertical dimension (m)  
(positive downward from the surface)

$t$  = time (d)

$C(h)$  = slope of the pF-curve or  $C(h) = d\Theta/dh$ , where  $\Theta$  is the volumetric soil water content ( $\text{m}^{-1}$ )

$S(h)$  = loss term which takes evaporation and horizontal surface runoff ( $\text{m}^3 \text{m}^{-3}$ ) into consideration.

The numerical solution of the equation has been solved with the element method as presented by Karvonen (1988). Parameters required for the quasi 3-D-model are described in Chapters 3.4.5, 3.4.6 and 3.5.

#### 3.4.4 Two-dimensional groundwater flow

The groundwater model is based on two well-known equations: Darcy's law and the equation of conservation of mass. The combination of these two equations results in a partial differential equation for unsteady flow:

$$S \frac{\partial H}{\partial t} = \frac{\partial}{\partial x} (KD \frac{\partial H}{\partial x}) + \frac{\partial}{\partial y} (KD \frac{\partial H}{\partial y}) + R - P \quad (22)$$

where

$K$  = hydraulic conductivity of the landfill for horizontal flow ( $\text{m d}^{-1}$ )

$D$  = saturated thickness of the landfill at time  $t$  (m)

$H$  = hydraulic head in the landfill at time  $t$  (m)

$R$  = net rate of recharge ( $\text{m d}^{-1}$ ) (negative if the flow of water is upward from the groundwater level)

$S$  = specific yield of the landfill ( $\text{m m}^{-1}$ )  
 $P$  = net rate of abstraction (e.g. drainage) ( $\text{m d}^{-1}$ ).

The net rate of recharge  $R$  is calculated with the one-dimensional model, or in other words  $R$ -term connects the one- and two- dimensional models together.

In this study the numerical solution of the groundwater flow equation is obtained using the finite element method. The equation (22), together with the appropriate initial and boundary conditions, is solved using the so-called Galerkin method. In using the finite element method, the flow region is subdivided into a network of triangular elements. The corners of these elements are the nodal points of the computation. In each element, the hydraulic head is approximated by linear shape functions and the values of  $H_n$  at nodal points.

The Galerkin finite element formulation of fluid flow through porous media leads to a system of a first-order linear differential equation of the form

$$[F]\{H(t)\} + [D]\{dH(t)/dt\} = \{Q\} \quad (23)$$

where

$[F]$  = stiffness matrix  
 $\{H\}$  = dependent variable vector (the hydraulic head in the landfill)  
 $[D]$  = capacity matrix and  
 $\{Q\}$  = flux vector representing sources and sinks.

The derivation of the coefficient matrices have been presented in Neuman *et al.* (1975). The solution of the equations uses the method described by Narisham and Witherspoon (1977, 1978).

### 3.4.5 Parameters required for the quasi 3-model

The so-called pF-curve-soil moisture retention curve-gives the relationship between volumetric soil moisture content ( $\text{m}^3 \text{m}^{-3}$ ) and matric potential  $\phi$  (m). Solid waste landfills can be considered a porous medium that consists of solid particles and pores that are either water-filled or air-filled. The total soil porosity or saturated water content,  $\Theta_s$  ( $\text{m}^3 \text{m}^{-3}$ ), depends on the packing density of the waste and the specific density of the individual soil particles. According to the literature review of Korfiatis *et al.* (1984), typical values of  $\Theta_s$  in landfills are about 0.50–0.60. Fig-

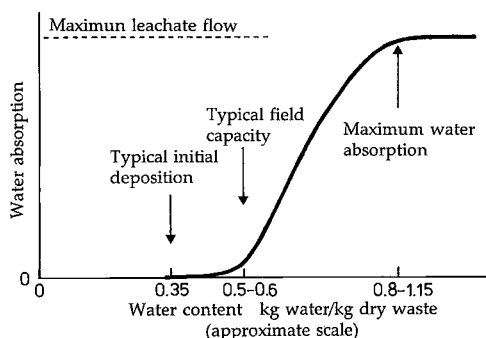


Fig. 24. An example of the change of leachate flow with moisture content for a landfill (Crawford and Smith 1985).

ure 24. shows an example of the change in leachate flow with moisture content of the landfill. For soil materials pF-curve can be determined from the particle size distribution.

An analysis of the relationship between soil moisture  $\Theta$  and matric potential  $\phi$  measured in the Netherlands suggests that  $\Theta = \Theta(\phi)$  can be satisfactorily given by the equation (Driessen 1986):

$$\Theta(\phi) = \Theta_s \exp\{-\mu [\ln(-\phi)]^2\} \quad (24)$$

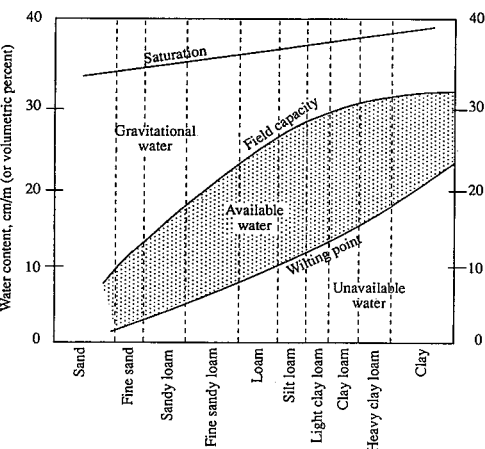
where

$\Theta_s$  = saturated water content when all the pores are filled with water ( $\text{m}^3 \text{m}^{-3}$ )  
 $\mu$  = soil parameter  
 $\phi$  = matric potential (m)

The indicative values of  $\Theta_s$  and  $\mu$  are given in Table 7. The equation (24) is a mathematical description of the soil pF-curve.

Figure 25 shows water-holding characteristics of soils. To illustrate the use of it consider a 0.6 m top soil cover of silty loam over a landfill.

- The field capacity =  $28 \text{ cm/m} \times 0.6 \text{ m} = 16.8 \text{ cm}$
- The wilting point =  $10.5 \text{ cm/m} \times 0.6 \text{ m} = 6.3 \text{ cm}$
- The storage capacity =  $(16.8 \text{ cm} - 6.3 \text{ cm}) = 10.5 \text{ cm}$ .



**Fig. 25.** Water-holding characteristics of soils (Lutton *et al.* 1979).

### 3.4.6 Water movement in soil

Darcy's law applies for the flow of water in saturated or unsaturated soil:

$$q = -K(\phi) \cdot \frac{dH/dz}{dz} \quad (25)$$

where

- $q$  = flow velocity ( $\text{m d}^{-1}$ )
- $K(\phi)$  = hydraulic conductivity of the soil (function of soil matric potential) ( $\text{m d}^{-1}$ )
- $H$  = hydraulic head ( $\phi + z$ ) (m)
- $z$  = vertical coordinate (vertical flow in soil (m)).

When  $\phi = 0$  cm, i.e. the soil is fully saturated,  $K(\phi)$  has its maximum value, i.e. saturated hydraulic conductivity. As  $\phi$  decreases, the larger pores will be emptied first and they do not contribute to the water flow. This implies that  $K(\phi)$  is continuously decreased as  $\phi$  decreases. The measurement of the relationship between  $\phi$  and  $K(\phi)$  is difficult and time-consuming. Therefore, mathematical descriptions are used to relate the matric potential  $\phi$  and hydraulic conductivity  $K(\phi)$ . The equations used are the following (Driessen 1986):

$$K(\phi) = K_s \cdot \exp(\alpha_K \cdot \phi) ; \phi \geq \phi_{\max} \quad (26)$$

$$K(\phi) = \alpha_K \cdot (-\phi)^{-1.4} ; \phi < \phi_{\max} \quad (27)$$

**Table 7.** Indicative values of  $\Theta_s, \mu, \phi_{\max}, K_s, a_K$  and  $\alpha_K$  for various soil texture classes (partly from Driessen 1986).

Soil type	Parameter					
	$\Theta_s \text{ m}^3 \text{ m}^{-3}$	$\mu$	$\phi_{\max} \text{ m}$	$K_s \text{ cm d}^{-1}$	$a_K$	$\alpha_K$
Top soil	0.40	0.033	200	26.5	16.4	0.0398
Drainage layer	0.395	0.100	70	1120	0.08	0.224
Filter	0.540	0.0042	80	0.22	4.86	0.038
Solid waste	0.55	0.07	70	1050	0.08	0.224
Coarse sand	0.395	0.10	70	1120	0.08	0.224
Fine sand	0.364	0.029	175	50	10.9	0.05
Loamy sand	0.439	0.033	200	26.5	16.4	0.0398
Fine sandy loam	0.504	0.021	290	12.0	26.5	0.0248
Silt loam	0.509	0.0185	300	6.5	47.3	0.0200
Loam	0.503	0.0180	300	5.0	14.4	0.0231
Loess loam	0.455	0.0169	130	14.5	22.6	0.049
Sandy clay loam	0.432	0.0096	200	23.5	33.6	0.0353
Silty clay loam	0.475	0.0105	170	1.5	36	0.0237
Clay loam	0.445	0.0058	300	0.98	1.69	0.0248
Light clay	0.453	0.0085	300	3.5	55.6	0.0174
Silty clay	0.507	0.0065	50	1.3	28.2	0.048
Heavy clay	0.540	0.0042	80	0.22	4.86	0.038
Peat	0.863	0.0112	50	5.3	6.82	0.1045

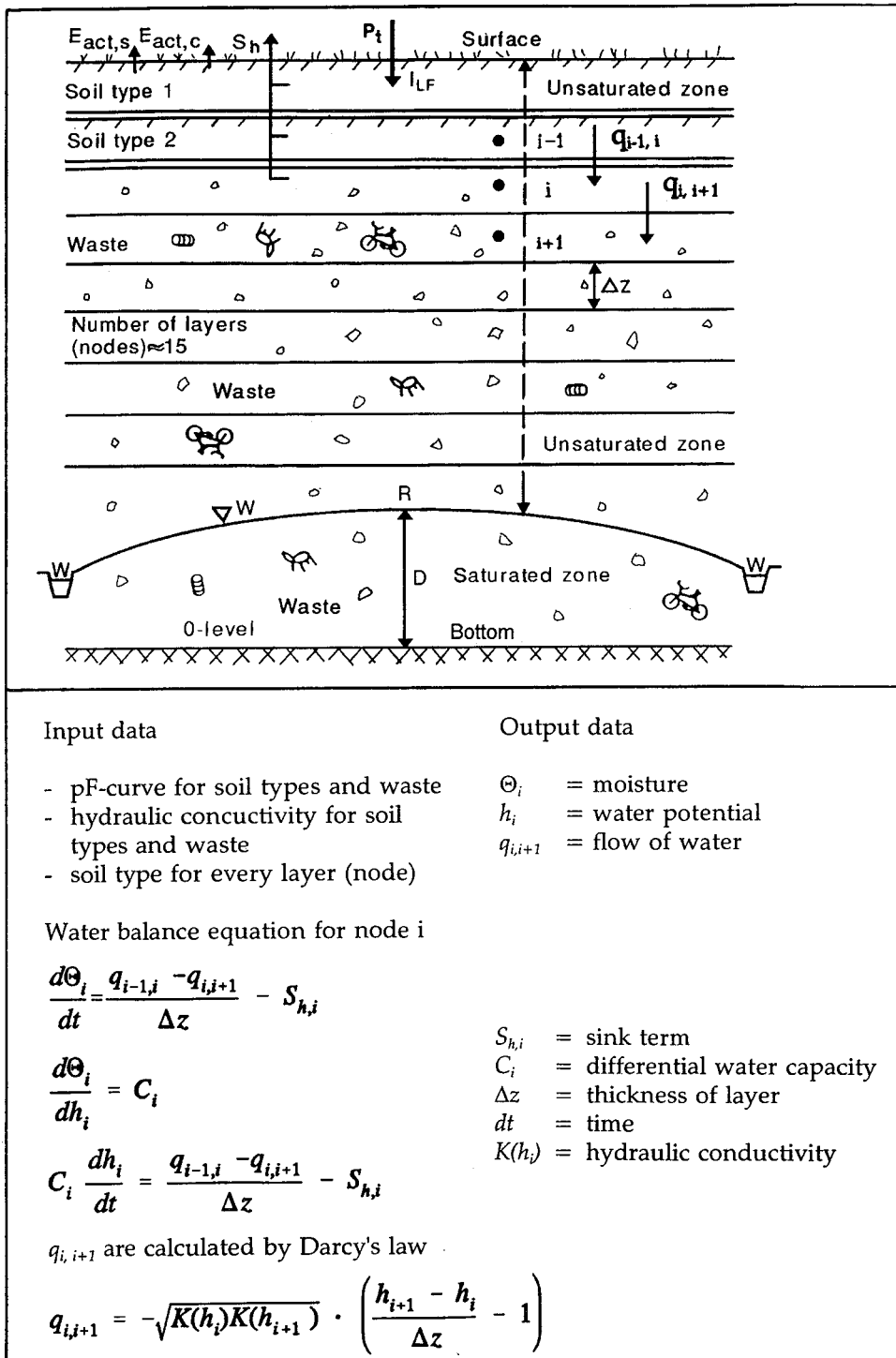
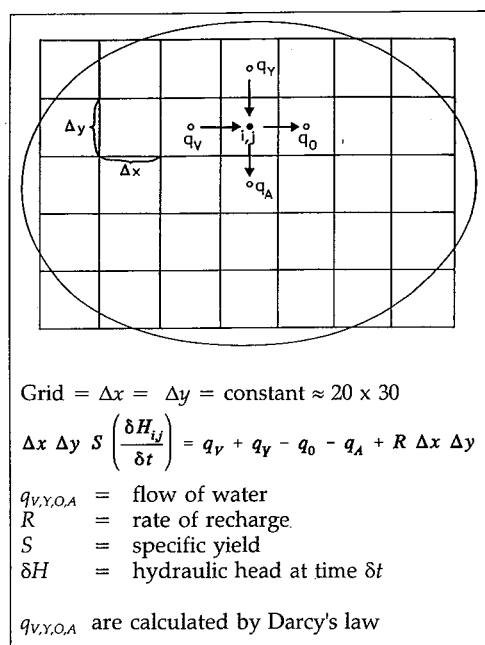


Fig. 26. Schematic figure of the calculations, input and output data of the 1-D model.



**Fig. 27.** Schematic figure of the calculation grid of the 2-D model.

where

- $K_s$  = saturated hydraulic conductivity (cm d<sup>-1</sup>)  
 $\phi_{\max}$  = matric potential limit (m)  
 $\alpha_K$  = soil parameter  
 $a_K$  = soil parameter.

The indicative values for all parameters are given in Table 7. Fig. 26 shows the schematic figure of the calculations, input and output data of the 1-D model. Fig. 27 shows the schematic figure of the calculation grids of the 2-D model. Fig. 28 shows the schematic flow chart of the quasi 3-D model.

### 3.5 Comparison of results given by LCAM the quasi 3-D model

#### 3.5.1 Numerical analysis with LCAM and the quasi 3-D model

This chapter compares the results given by the more exact, quasi 3-D model (presented in Chap. 3.4) to the results obtained by LCAM (presented in Chap. 3.3). Chapter 3.5.2 deals with uncertainty sources of the quasi 3-D model.

In the comparison, the initial data needed by the

3-D model were, as initial data, the pF-curve of the soil and the hydraulic conductivity of soil as a function of the soil moisture. The numerical analysis was done with two different soil types, and the initial data needed is shown in Fig. 29. Other parameters needed were: the thickness of the surface layer, 600 mm, and its hydraulic conductivity which was  $10^{-5.3} \text{ m s}^{-1}$ , the thickness of the hydraulic barrier, 300 mm, and its hydraulic conductivity which was between  $10^{-7.3}$ – $10^{-9.3} \text{ m s}^{-1}$ . The calculations were done with the hydrological data measured in the Kaisaniemi area of Helsinki in the years 1981 and 1983. The first year was rainier than normal (annual precipitation 790 mm) and the latter drier than normal (annual precipitation 600 mm).

In the calculations different components of the water balance were compared to each other calculated by the 3-D model and LCAM. The main attention was paid to the infiltration, surface runoff, surface layer runoff and the comparison of the sum of the above components.

Figure 30 shows the components of the water balance calculated by the 3-D model and LCAM with the hydrological data for 1981. The hydraulic conductivity of the hydraulic barrier was  $10^{-8.3} \text{ m s}^{-1}$  which represented the hydraulic conductivity of a rather well-constructed hydraulic barrier. The results calculated by LCAM were very close to the results of the 3-D model. The greatest differences were in the numerical analysis of surface runoff: the 3-D model gave 19.9 cm and LCAM 18.2 cm per year. Infiltration through the wastes was in the 3-D model 11.6 cm per year and in LCAM 12.7 cm per year. The sums of the three components of water balance were almost the same: the 3-D model gave 37.9 cm per year and LCAM 37.7 cm per year.

Figure 31 shows the same numerical analysis when the hydraulic conductivity of the hydraulic barrier was  $10^{-9.3} \text{ m s}^{-1}$ , which was a very tight hydraulic barrier. Results analysed by LCAM and 3-D models were almost the same in this case also: the reduction of hydraulic conductivity decreased the infiltration to the wastes substantially: the 3-D model gave 1.4 cm per year and LCAM 1.6 cm per year. The surface runoff increased instead: the 3-D model gave 28.2 cm per year and LCAM 27.2 cm per year.

Figure 32 shows the values of the components of the water balance when the hydraulic conductivity of the hydraulic barrier was  $10^{-8.0} \text{ m s}^{-1}$ . The results analysed with the 3-D model and LCAM were almost the same. The infiltration to the

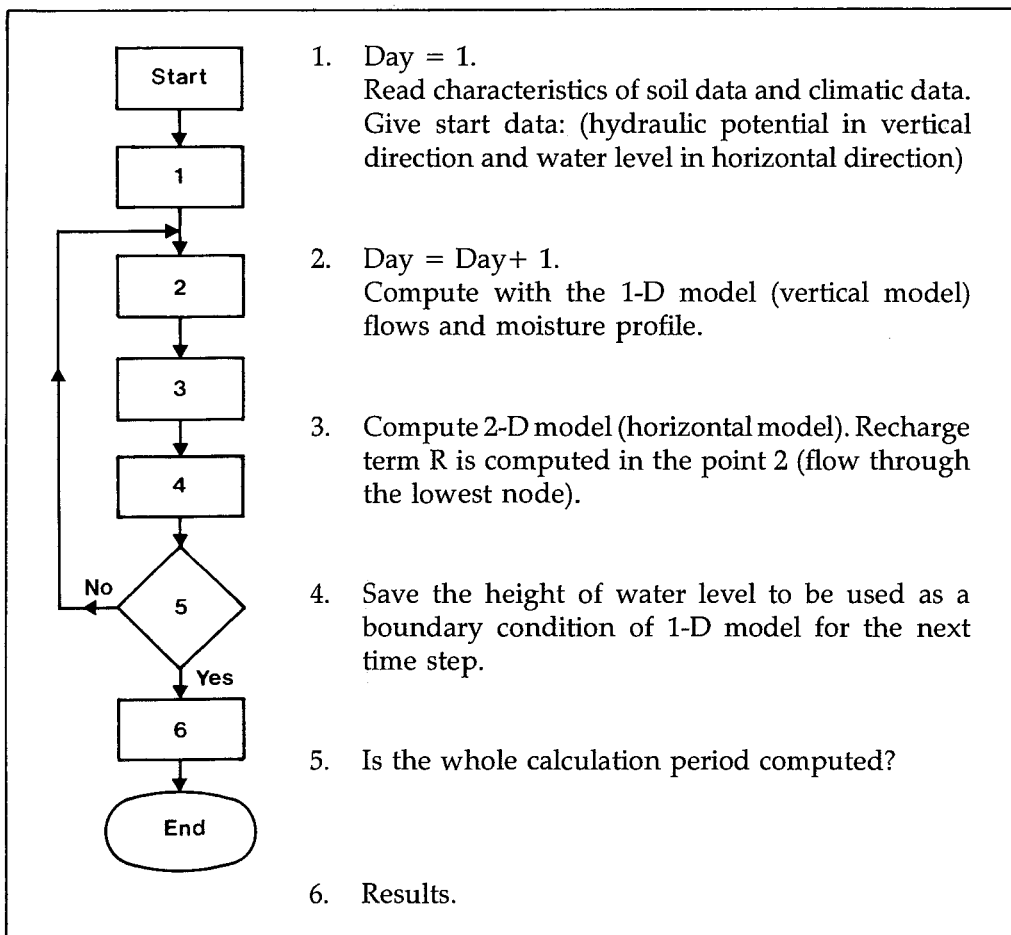


Fig. 28. Schematic flow chart of the quasi 3-D model.

wastes in the 3-D model was 19.6 cm per year and in LCAM 21.1 cm per year. Surface runoff was less than earlier: in the 3-D model it was 13.6 cm per year and in LCAM 11.7 cm per year.

When the hydraulic conductivity of the hydraulic barrier increased to the value  $10^{-7.3} \text{ m s}^{-1}$ , surface runoff ceased almost totally and nearly half of the annual precipitation infiltrated to the wastes. In the 3-D model infiltration was 36.3 cm per year and in the LCAM 36.9 cm per year. The results calculated with both models were almost the same in this case also. Surface runoff in the 3-D model was 2.0 cm and in LCAM 2.4 cm. The components of the water balance are shown in Fig. 33.

Figure 34 shows the components of the water balance using the hydrological data for 1983. Hydraulic conductivity was  $10^{-8.3} \text{ m s}^{-1}$ . The infiltra-

tion to the wastes was only 7.1 cm in the 3-D model and it was 7.6 cm in LCAM. The surface runoff in both models was very small, it was 2.5 cm in the 3-D model and 1.9 cm in LCAM. The results calculated with both models were very similar to each other.

Figure 35 shows the moisture contents of soil at three different depths calculated with the 3-D model and LCAM. The results analysed with LCAM were not significantly different from the results analysed with the 3-D model.

Figure 36 shows the depths of the saturated layer analysed with the 3-D model and LCAM using the hydrological data for 1981. Also in this case LCAM described the dynamics of the phenomenon very reliably. Fig. 37 gives the results of Fig. 36, so that the x-axis shows the depths of the



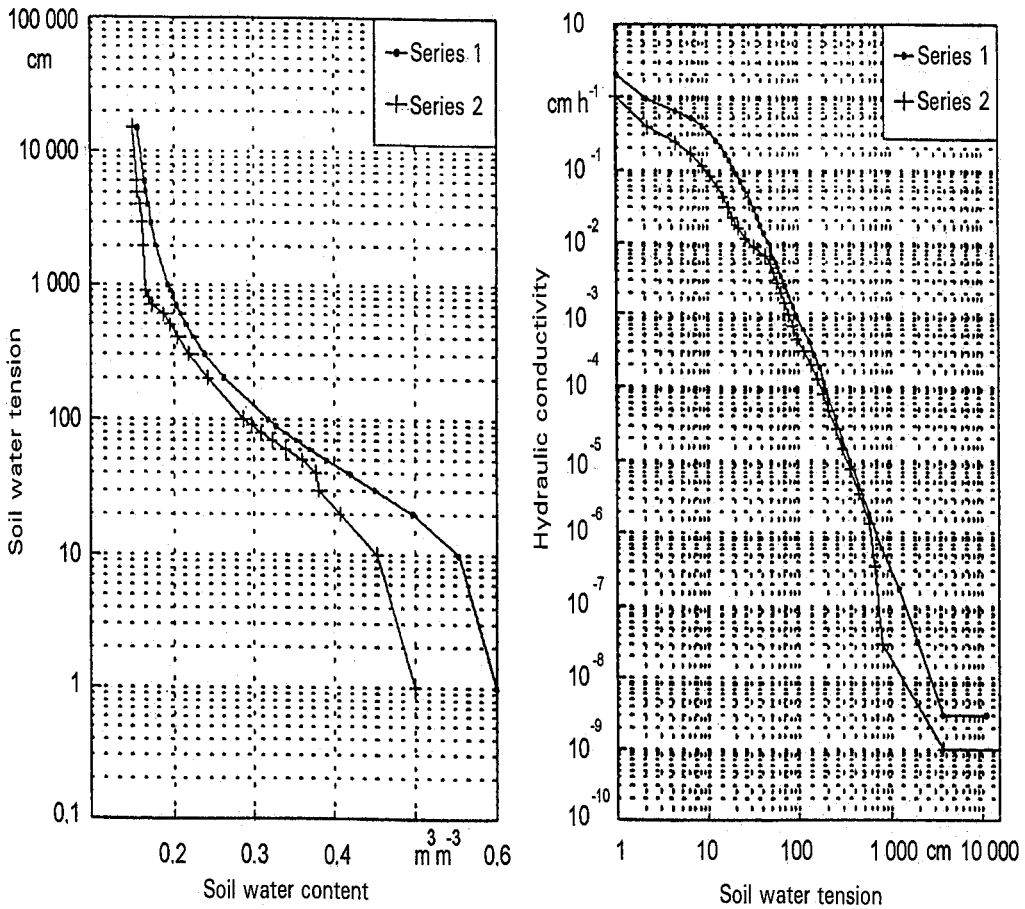


Fig. 29. Properties of soils needed in the calculations of the pF-curve and hydraulic conductivity as a function of moisture for the two different types of surface layers. Modified from Driessen (1986).

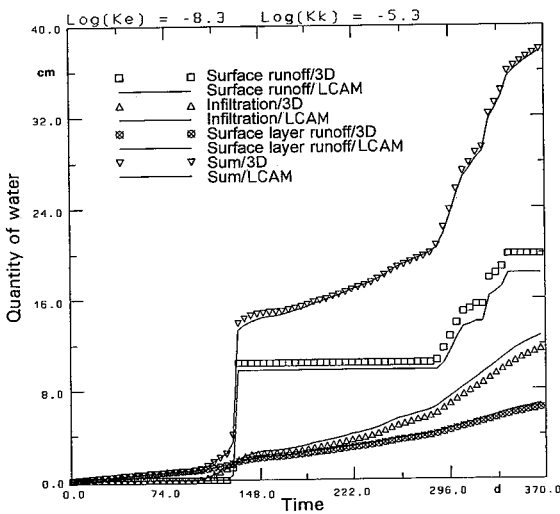


Fig. 30. Comparison of the components of the water balance analysed with the quasi 3-D model and LCAM using the hydrological data for 1981. The hydraulic conductivity of the hydraulic barrier is  $10^{-8.3} \text{ m s}^{-1}$  and the hydraulic conductivity of the surface layer is  $10^{-5.3} \text{ m s}^{-1}$ . Sum = surface runoff + infiltration to the wastes + surface layer runoff.

saturated layer calculated with the 3-D model and the y-axis shows the results analysed with LCAM.

As a conclusion from the numerical analysis it can be said that components analysed with the LCAM have very minor differences with the components analysed with the 3-D model. Therefore LCAM is sufficiently accurate and it is not necessary to use the complicated quasi 3-D model. However, in future it is worthwhile to monitor the results obtain by LCAM and to continue the testings in different situations because in this work it could be tested only in a limited scale.

### **3.5.2 Uncertainty sources of the quasi 3-D model**

The complicated model used in this study is a so called quasi 3-D model, and in its solution the unsaturated zone is calculated with the 1-D vertical model and the fully saturated zone with the 2-D groundwater model. These two models are connected with the boundary conditions e.g. the depth of the groundwater level calculated by the 2-D model is the lower boundary condition of the 1-D model. The fixing of the lower boundary condition to a known level means that the quantity of water flowing through a lower surface can be calculated, and this quantity of water is the recharge needed in the 2-D model in the calculation for the following time-step.

The solution of the vertical 1-D model is based on the solution of Richards' equation done numerically by the element method. The numerical solution of the 1-D vertical model is tested with several test examples (Karvonen 1988). The 2-D model is tested with examples presented in the literature (Karvonen 1993).

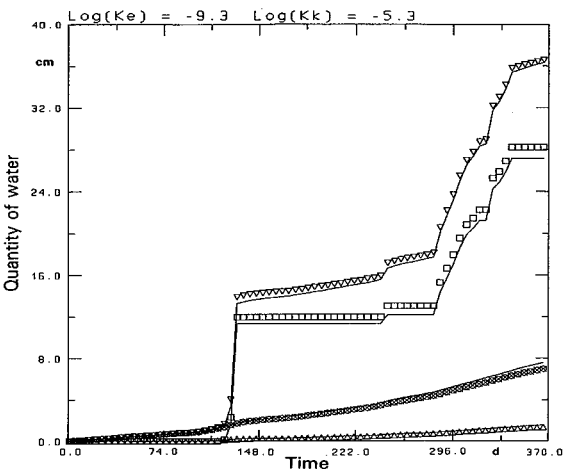
In the calculation of the vertical part model input data from the waste body and upper surface layers the following data are needed:

- pF-curve or relation between water content and matric potential
- hydraulic conductivity of the soil as a function of moisture (or field capacity)

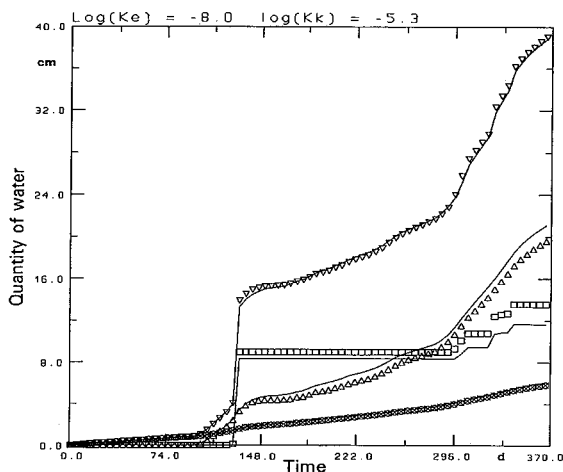
The above parameters only describe at best the average quality of wastes because exact data from the whole landfill is impossible to obtain. The complicated 3-D model is only used in the situation where results of the 3-D model are used as so called "exact measurements" in the testing of

LCAM. Input data presented in Korfiatis *et al.* (1984) are used in the calculations of the 3-D model concerning waste bodies as values for pF-curves and hydraulic conductivities. LCAM does not need values of field capacity and hydraulic conductivity as input data.

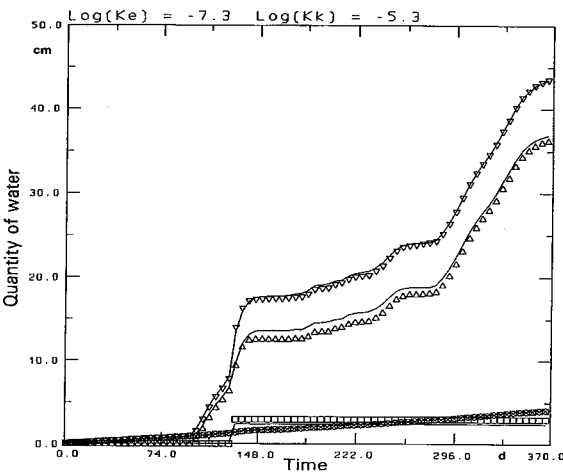
The other primary error source the of 3-D model are the boundary conditions of the 2-D model. One should know conditions of the water level in the surroundings of the landfill (surrounding ditch) or know the discharges from the landfill. Discharges are, however, not known in practical situations and so the only realistic boundary condition is to use the groundwater level of the surrounding ditch. However, these water levels are not usually measured and it must be estimated that the water level is at the same level as the bottom of the surrounding ditch. This boundary condition prevents a situation where the seepage face is already on the slope. Due to the above uncertainties, the 3-D model cannot give very exact results in practical situations and this means that the conclusions are the same as earlier: the 3-D model can only be used in the testing of LCAM when supposing that the groundwater level behaves as if there is no seepage level. LCAM does not need the water levels in the surroundings of the landfill as input parameters.



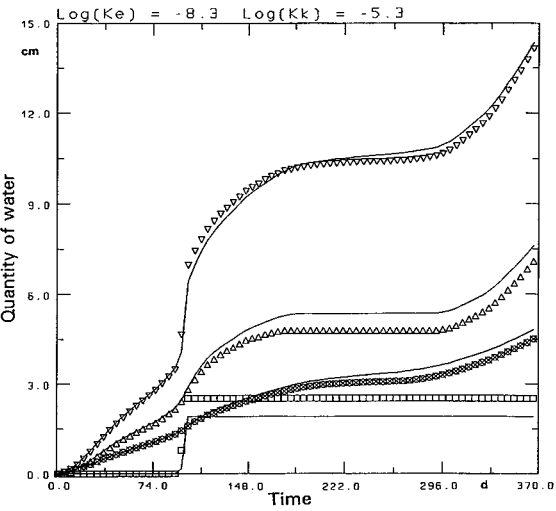
**Fig. 31.** Comparison of the components of the water balance analysed with the quasi 3-D model and LCAM using the hydrological data for 1981. The hydraulic conductivity of the hydraulic barrier is  $10^{-9.3} \text{ m s}^{-1}$  and the hydraulic conductivity of the surface layer is  $10^{-5.3} \text{ m s}^{-1}$ . Sum = surface runoff + infiltration to the wastes + surface layer runoff. Symbols are same as in Fig. 30.



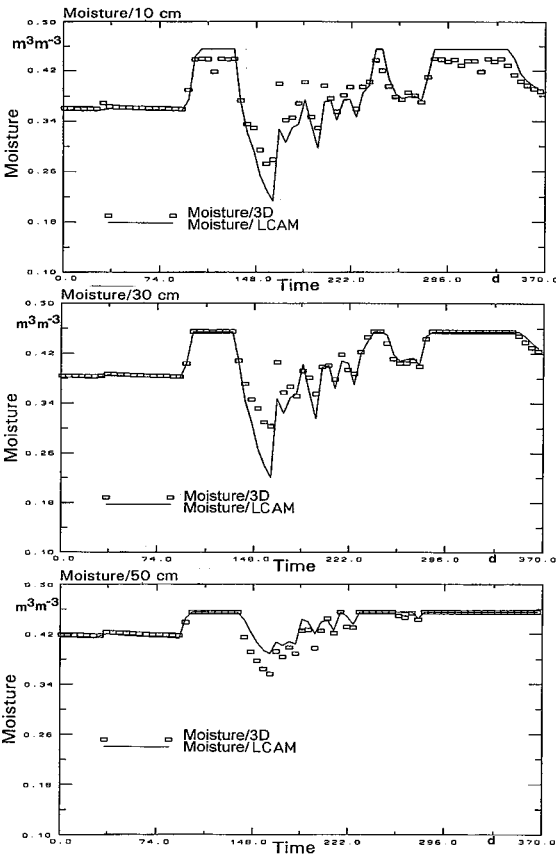
**Fig. 32.** Comparison of the components of the water balance analysed with the quasi 3-D model and LCAM using the hydrological data for 1981. The hydraulic conductivity of the hydraulic barrier is  $10^{-8.0} \text{ m s}^{-1}$  and the hydraulic conductivity of the surface layer is  $10^{-5.3} \text{ m s}^{-1}$ . Sum = surface runoff + infiltration to the wastes + surface layer runoff. Symbols are same as in Fig. 30.



**Fig. 33.** Comparison of the components of the water balance analysed with the quasi 3-D model and LCAM using the hydrological data for 1981. The hydraulic conductivity of the hydraulic barrier is  $10^{-7.3} \text{ m s}^{-1}$  and the hydraulic conductivity of the surface layer is  $10^{-5.3} \text{ m s}^{-1}$ . Sum = surface runoff + infiltration to the wastes + surface layer runoff. Symbols are same as in Fig. 30.



**Fig. 34.** Comparison of the components of the water balance analysed with the quasi 3-D model and LCAM with the hydrological data for 1983. The hydraulic conductivity of the hydraulic barrier is  $10^{-8.3} \text{ m s}^{-1}$  and the hydraulic conductivity of the surface layer is  $10^{-5.3} \text{ m s}^{-1}$ . Sum = surface runoff + infiltration to the wastes + surface layer runoff. Symbols are same as in Fig. 30.



**Fig. 35.** Moisture content of soil at the depths of 10, 30 and 50 cm, analysed with the quasi 3-D model and LCAM using the hydrological data for 1981.

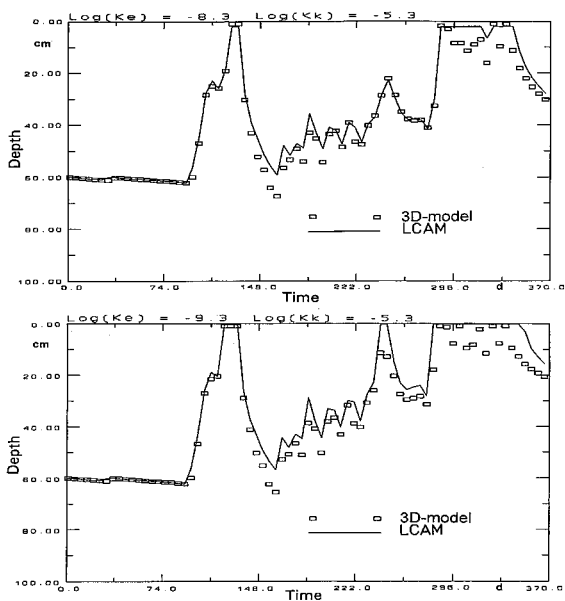


Fig. 36. Depth of the saturated layer (distance from the surface) calculated with the quasi 3-D model and LCAM using the hydrological data for 1981.

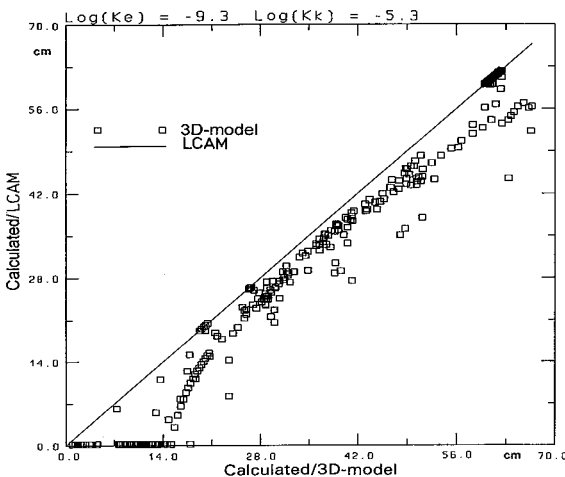


Fig. 37. Comparison of the depths of saturated layers calculated with the quasi 3-D model and LCAM.

4 Testing of LCAM

4.1 Background

The testing of LCAM was two phased. The first phase included the field investigations of test landfills and the second phase the comparison of the quantities of leachate waters measured in the test landfills and calculated by LCAM.

In planning the testing of LCAM, almost all landfills in Finland were surveyed and their suitability for testing purposes was investigated and estimated. From the survey, the Seutula, Karanoja Hämeenlinna, Silmäsuo Kuopio and Kyöpelä Eura landfills were chosen (Fig. 38). It was seen clearly in the survey that at only a few landfills in Finland had the quantities of leachate waters been measured with a high enough accuracy, and for sufficiently long periods, to test LCAM.

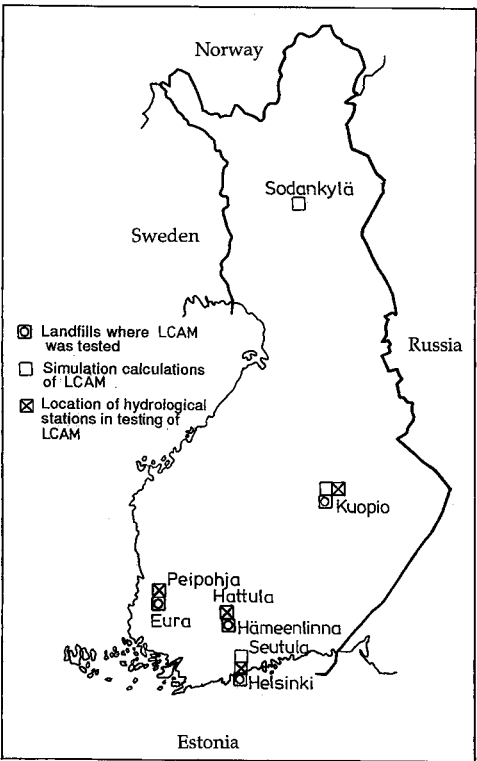


Fig. 38. Testings and simulations of LCAM and the location of the hydrological observation stations.

4.2 Field investigations of test landfills

In the first phase of testing LCAM the aim of the field investigations was to investigate two things. They were the height of the water level in the landfills and the hydraulic conductivity of surface parts of the test landfills. Groundwater tubes were installed into the landfills and weight sounding tests were done at the same time. Water level heights were measured weekly, and in the melting period every other day, between 30.1.–30.11.1992. Disturbed samples were taken from the surface parts of landfills for laboratory investigations (Table 8).

Weight sounding tests, installation of groundwater tubes and sampling were done in the Seutula and Eura landfills with a multiple-use drill (A-Sondi 304). In Hämeenlinna, investigations were done with a multiple-use drill (A-Sondi 504) and in Kuopio with a multiple-use drill (Borro). The investigation standards were the same as mentioned in App. 1.

The groundwater tubes were standard water tubes, which had a sieve part (inner diameter 26 mm, length of sieve 1–2 m, diameter of holes 3 mm). Soil samples were taken with the sampler of a multiple-use drill (auger-point, blade diameter 65 mm, length of sample taker 200 mm, inner diameter 25 mm). The grain size, water content, dry unit weight and hydraulic conductivity of the samples were investigated by the standard methods mentioned in App. 1.

Table 8. The height and the area of the test landfills of LCAM and the thickness and hydraulic conductivity of the surface layers.

Landfill	Height m	Area hectare	Surface layer	
			thickness cm	hydraulic conductivity m s <sup>-1</sup>
Seutula	31	16.4	20–40	10 <sup>-5.5</sup> –10 <sup>-8.6</sup>
Karanoja/ Hämeenlinna	15	8	50–100	10 <sup>-6.3</sup> –10 <sup>-6.6</sup>
Silmäsuo/ Kuopio	20	12	50–100	10 <sup>-6.2</sup> –10 <sup>-8.2</sup>
Kyöpelä/ Eura	10	1.3	20–50	10 <sup>-5.8</sup> –10 <sup>-7.9</sup>

On the Seutula landfill, eight weight sounding tests were done on the investigation line 1 (PL 0, PL 50, PL 100, PL 150, PL 200, PL 300, PL 400) and five weight sounding tests were done on the investigation line 2 (PL 0, PL 50, PL 100, PL 150, PL 200). The depths were 0.7–1.2 m. The lengths of the investigation lines were 200 and 400 m. Totally 31 samples were taken from the surface parts of the landfill from depths of 0.1–0.9 m. Five groundwater tubes were installed in the landfill at the depths of 8.8–11.0 m (PV 1, PV 2, PV 3, PV 4, PV 5) (Fig. 39).

On the Hämeenlinna landfill, six weight sounding tests were done on the investigation line 1 (PL 0, PL 50, PL 150, PL 200, PL 250, PL 285) and five weight sounding tests were done on the investigation line 2 (PL 0, PL 50, PL 100, PL 150, PL 170). The depths were 2.2–4.0 m. The lengths of the investigation lines were 170 and 285 m. Eight samples were taken from the surface parts of the landfill from the depths of 0.0–0.6 m. Seven groundwater tubes were installed in the landfill at the depths of 9.4–11.0 m (PV 1, PV 2, PV 3, PV 4, PV 5, PV 6, PV 7) (Fig. 40).

On the Kuopio landfill, totally 10 weight sounding tests were done on the investigation line 1 (PL 30, PL 50, PL 85, PL 150, PL 200, PL 250, PL 300, PL 350, PL 400, PL 420) and six weight sounding tests were done on the investigation line 2 (PL 25, PL 50, PL 85: the same as on line 1, PL 100, PL 150, PL 181). The depths were 2.4–5.0 m. The lengths of the investigation lines were 185 and 420 m. Totally 85 samples were taken from the depths of 0.0–4.0 m. Seven groundwater tubes were installed in the landfill at the depth of 12.3–14.0 m (PV 1, PV 2, PV 3, PV 4, PV 5, PV 6, PV 7, PV 8) (Fig. 41).

On the Eura landfill, seven weight sounding tests were done on the investigation line 1 (PL 0, PL 25, PL 50, PL 75, PL 100, PL 125, PL 150) and five weight sounding tests were done on the investigation line 2 (PL 0, PL 30, PL 80, PL 100: the same as on line 1, PL 130). The depths were 0.6–5.2 metres. The lengths of the investigation lines were 130 and 150 metres. Totally 33 samples were taken from the surface parts of landfills from depths of 0.1–0.4 m. Three groundwater tubes were installed at the depth of 7.5–8.0 m (PV 1, PV 2, PV 3) (Fig. 42).

### 4.3 Results of the field investigations of the test landfills

The water levels in the test landfills are shown in Figs. 39, 40, 41 and 42. According to the results of the measurements the water levels in the landfills were far from the surfaces of the landfills in all seasons. The water levels were, on average, midway between the top and the bottom of the landfills. e.g. 7.5–14.0 m from the surfaces of the landfills depending on the total height of the landfills. At the edges of the landfills the water levels were at the level of the surrounding ditches.

On the basis of the results of the water level measurements in the landfills it can be said that the fundamental supposition of LCAM is correct (Chapter 3.4.1) e.g. the spreading of water in wastes is not modelled at all, but the result given by the model is the amount of water, which infiltrates through the surface structures into the wastes. Also according to Ettala (1987a), the infiltration into the landfills is mostly over  $1 \text{ mm min}^{-1}$  and after penetrating through hydraulic barrier, the spreading of water in wastes is quick compared to the heaviness of precipitation and the snow melt. This means that after rainfall the surface layer is at once in a hydraulic balance state. This is due to, among other things, the way of construction of Finnish landfills in which leachate water can freely discharge into the surrounding ditches for in landfills there is a lot of free void.

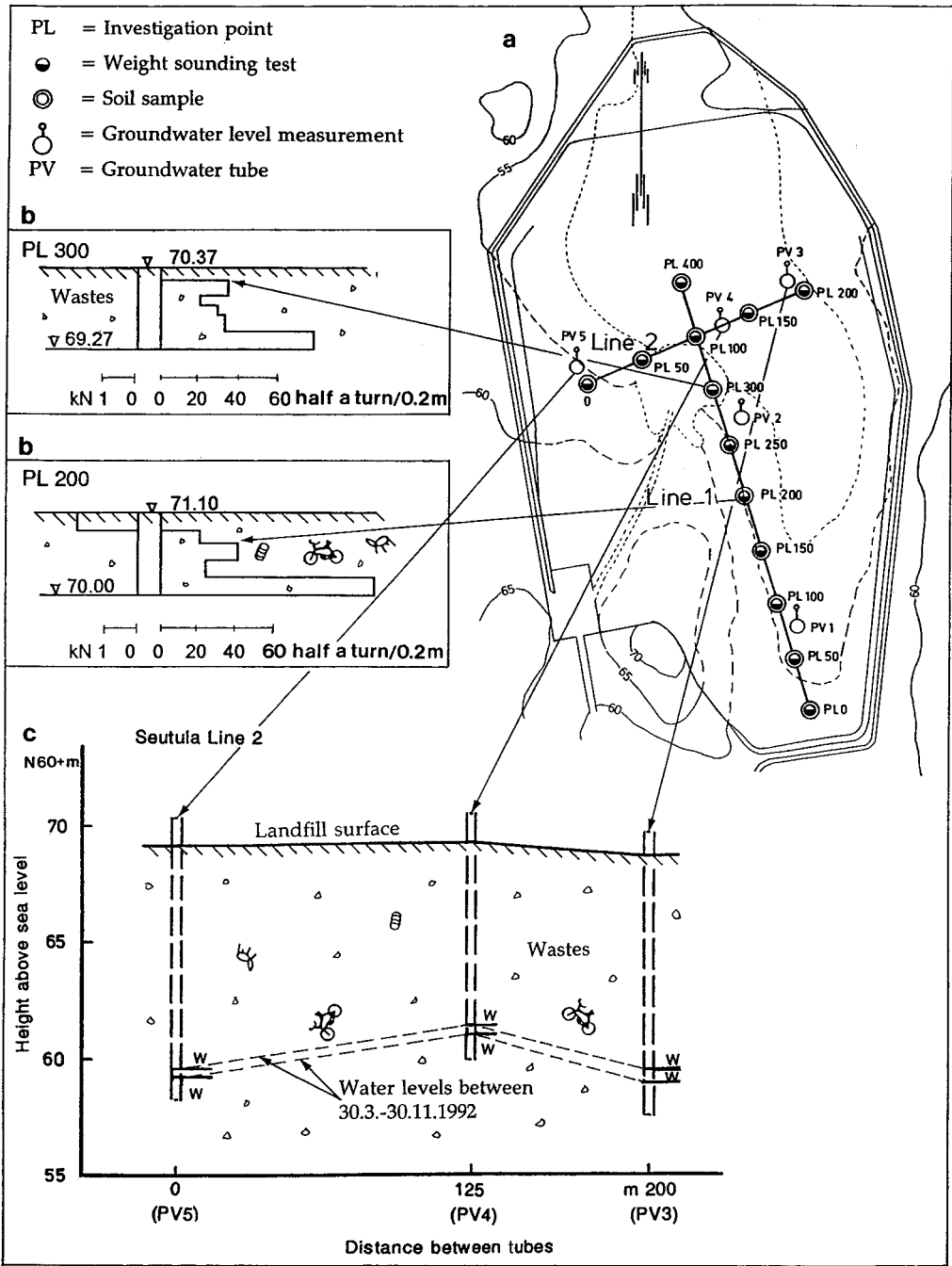
The hydraulic conductivity of the samples taken from the surface parts of the landfills varied between  $10^{-5.5}$  and  $10^{-8.6} \text{ m s}^{-1}$  (Table 8).

It must be noted that the rinsing of groundwater tubes was done twice during the testing period at all landfills. Therefore, it could be supposed that there were, for example, no blockages in the sieve parts of the groundwater tubes.

### 4.4 The quantities of the leachate waters measured in the test landfills and calculated by LCAM

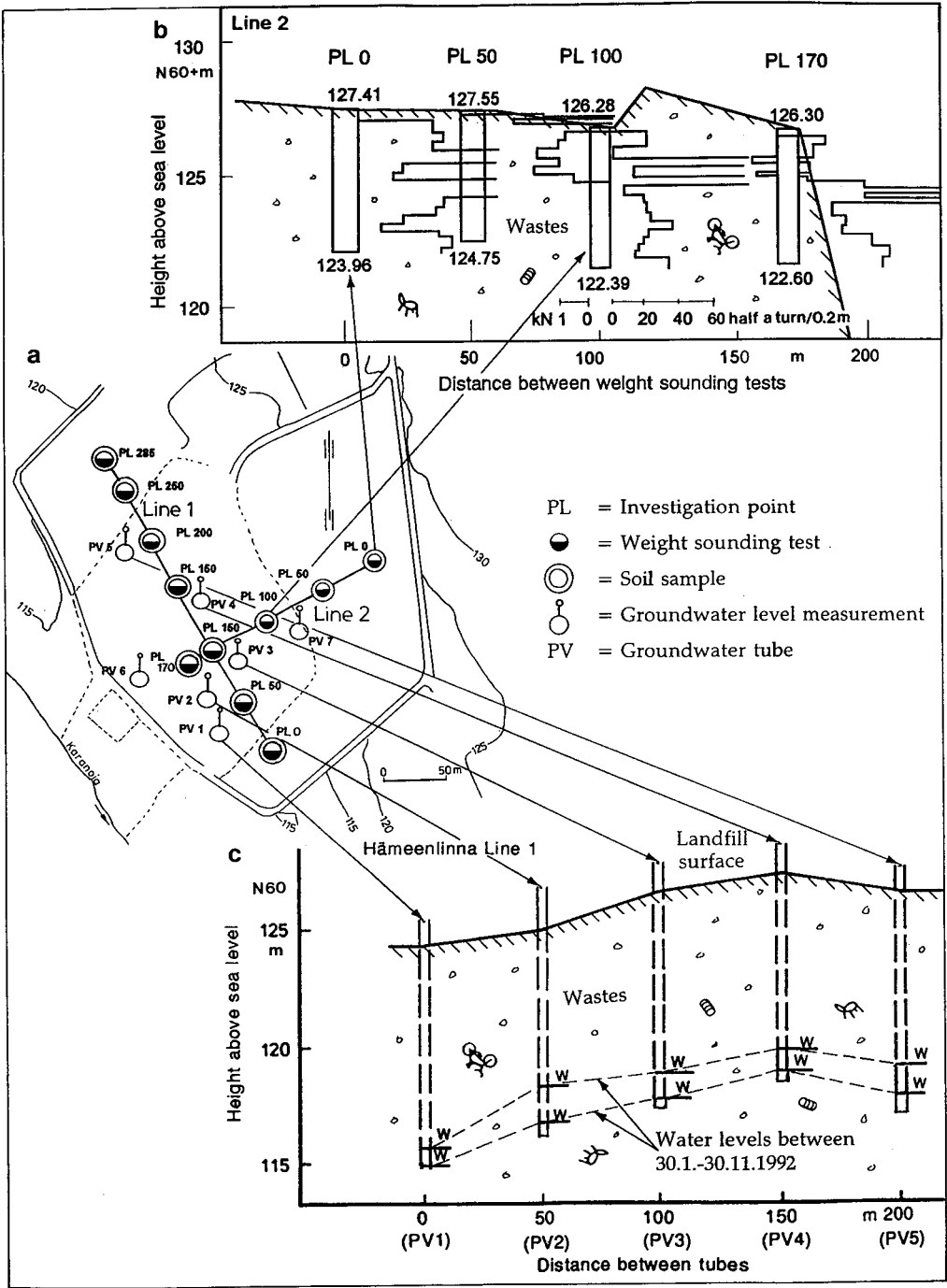
#### 4.4.1 Background

In the second phase of the testing of LCAM the aim was to compare the quantities of leachate waters measured at the landfills and calculated by LCAM. It must be noted that the quantities of leachate waters were not measured in this research but were done by the landfill owners, consultants or other parties.

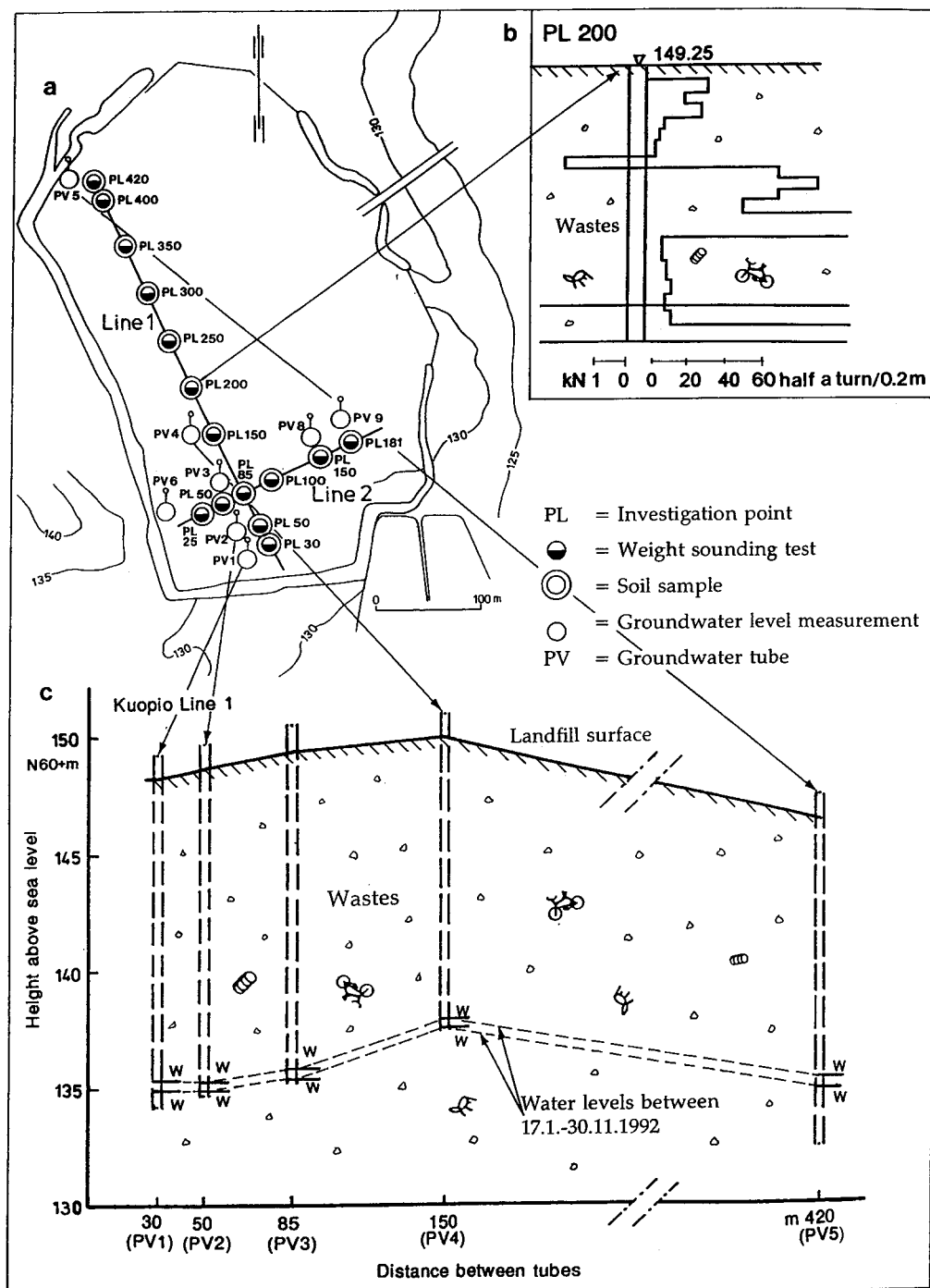


**Fig. 39.** Draft description of field investigations at the Seutula landfill in the testing of LCAM. Investigation lines (a), examples of weight sounding tests (b) and water levels between 30.3.-30.11.1992 (c). Pieces of concrete and other hard material made weight sounding tests difficult at almost all investigation points. Figure is to illustrate the procedure of testing.





**Fig. 40.** Field investigations at the Hämeenlinna landfill in the testing of LCAM. Investigation lines (a), examples of weight sounding tests (b) and water levels between 30.1.–30.11.1992 (c). Pieces of concrete and other hard material made weight sounding tests difficult at almost all investigation points.



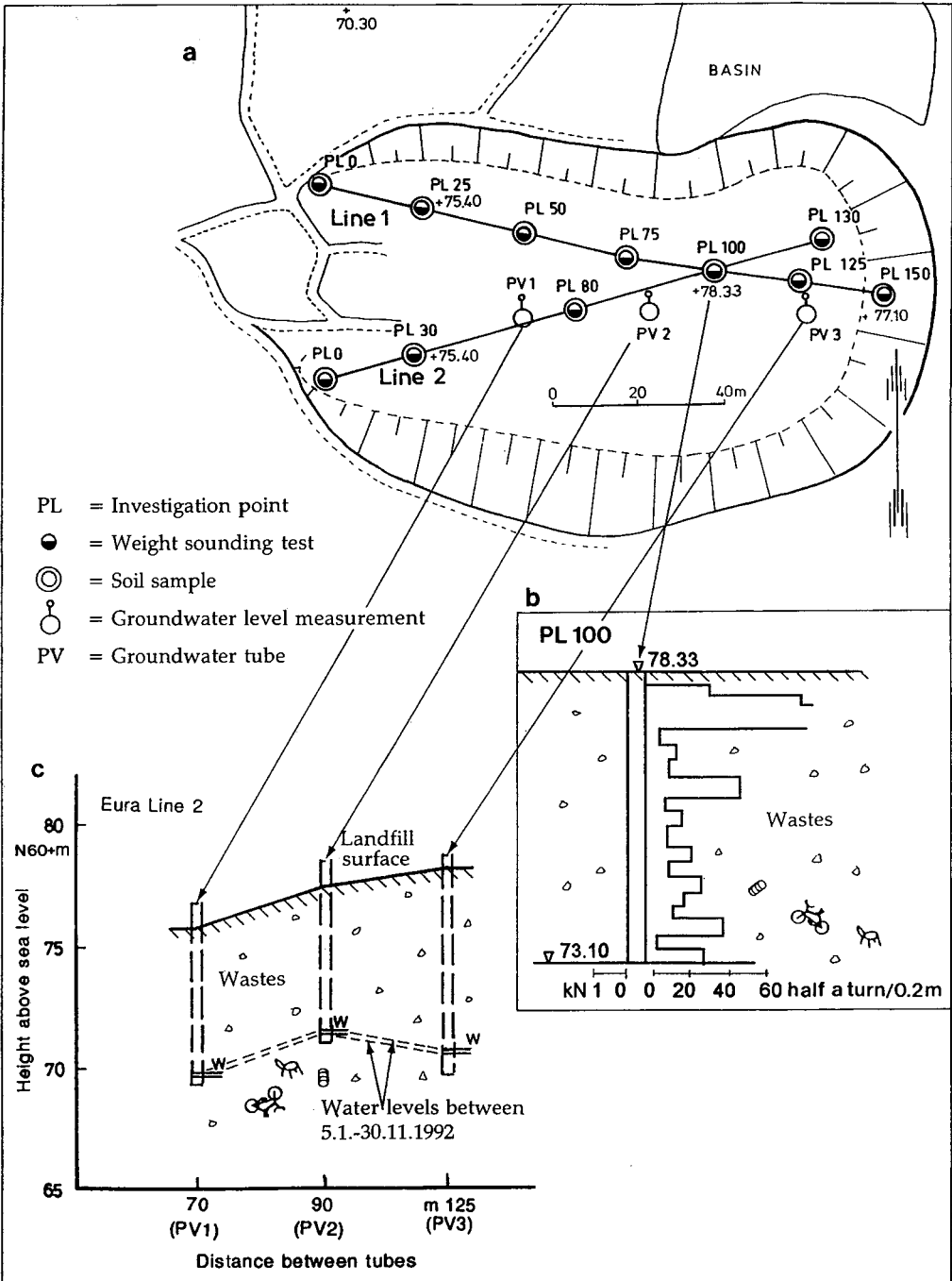


Fig. 42. Field investigations at the Eura landfill in the testing of the LCAM. Investigation lines (a), an example of weight sounding tests (b) and water levels between 5.6.-30.11.1992 (c). Pieces of concrete and other hard material made weight sounding tests difficult at almost all investigation points.

#### **4.4.2 The measurements of leachate waters in the landfills and their error sources**

##### *Seutula landfill*

In the Seutula landfill the quantities of leachate waters were measured with a magnetic water gauge, which generally gives exact results. However, the outer ditch of the landfill could have been iced over occasionally and this might have lead to outside water sometimes flowing into the surrounding ditch of the landfill. The errors caused by this could have been a maximum of 3 000 m<sup>3</sup> annually or 4–6 % of the leachate water depending on the annual precipitation. The second source of error was due to the erosion failure in the dam of the leachate basin in the testing period. The error caused by it was a maximum of 3 000 m<sup>3</sup> annually or 4–6 % of the leachate waters depending on the annual precipitation.

##### *Hämeenlinna landfill*

In the Hämeenlinna landfill the quantities of leachate waters were measured by the operating time of a leachate removal pump. The accuracy of the pump was checked by volume measurements and the errors caused by it were below 10 % of the annual total quantity of leachate waters. Below the landfill there was also a small spring which sometimes discharged small quantities of spring water to the subsurface drains of the landfill. The effects of the spring on the quantities of leachate waters were estimated to be about 5 %.

##### *Kuopio landfill*

In the Kuopio landfill the quantity of the leachate waters were measured with a water gauge. In addition to that, checking measurements from the measurement weir had been done when the water samples were taken. The measurements of leachate waters were considered reliable and precise.

##### *Eura landfill*

In the Eura landfill the quantities of the leachate waters were measured by measuring the discharge of the leachate basin pipe in to a container. The measurements were made three times a

week and an average value of several measurements was taken. The check measurements were done four times per year by the water protection association of South-West Finland. The measurements were fairly reliable with small flows but with greater flows the accuracy was not as high. Errors in the measurements were considered to be about 10–20 % of the annual quantity of the leachate waters.

#### **4.4.3 Circumstances of the measurements of the leachate waters**

At the test landfills the measurements of the leachate waters were not done under controlled circumstances and impreciseness of the measurements has caused uncertainty in the results. Compared to the earlier research results, for example, Knox and Gronow (1993) and Melchior *et al.* (1993), the quantities of leachate waters in this research were higher. Some of the differences could be accounted for by the measurements being done under more controlled or different circumstances in their measurements. A more controlled way of testing would have been to measure separately infiltration, surface runoff and subsurface layer runoff but under the test circumstances of the research this was impossible.

#### **4.4.4 Input data in the testing of LCAM**

The testing of LCAM was done with the observation and research data of the test landfills in a time period of 3–4 years during 1987–1992. Fig. 43 shows means, medians, maximum and minimum hydraulic conductivities of the surface parts of the test landfills. Three different values of hydraulic conductivity were used in the testing (Fig. 44) based on the laboratory measurements of the samples taken from the surface parts of the landfills. This was done to determine the sensitivity of LCAM to the changes in hydraulic conductivities of surface structures. The surface structures of the landfills in the model testing are shown in Fig. 44. Table 9 shows, as a summary of simulation periods, annual quantities of leachate waters and hydraulic conductivities used in the simulation. The other values of the input data are shown in App. 3.

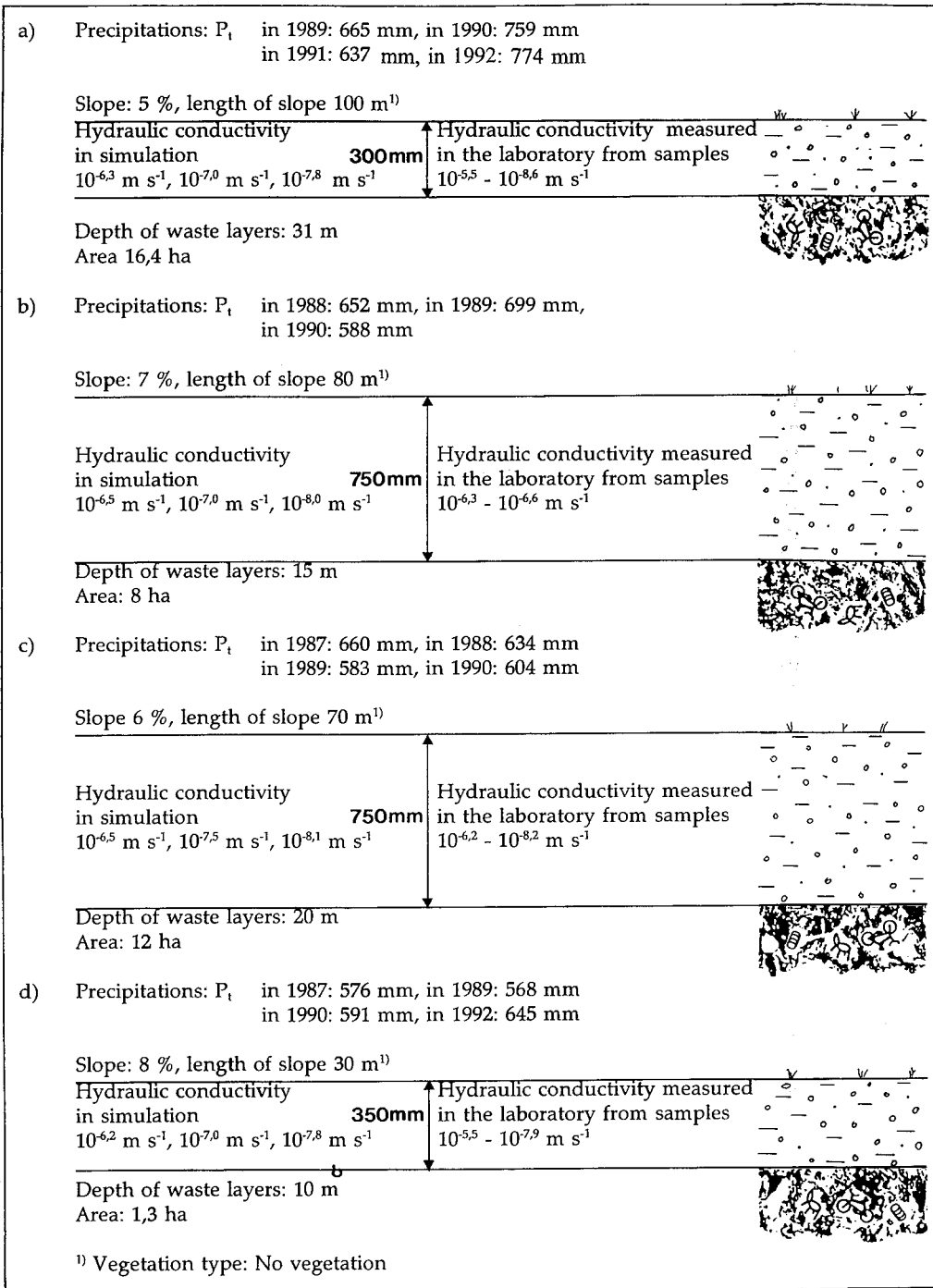


Fig. 44. Surface structures of landfills in the testing of LCAM. Seutula (a), Hämeenlinna (b), Kuopio (c) and Eura (d). Other input data are shown in App. 3.

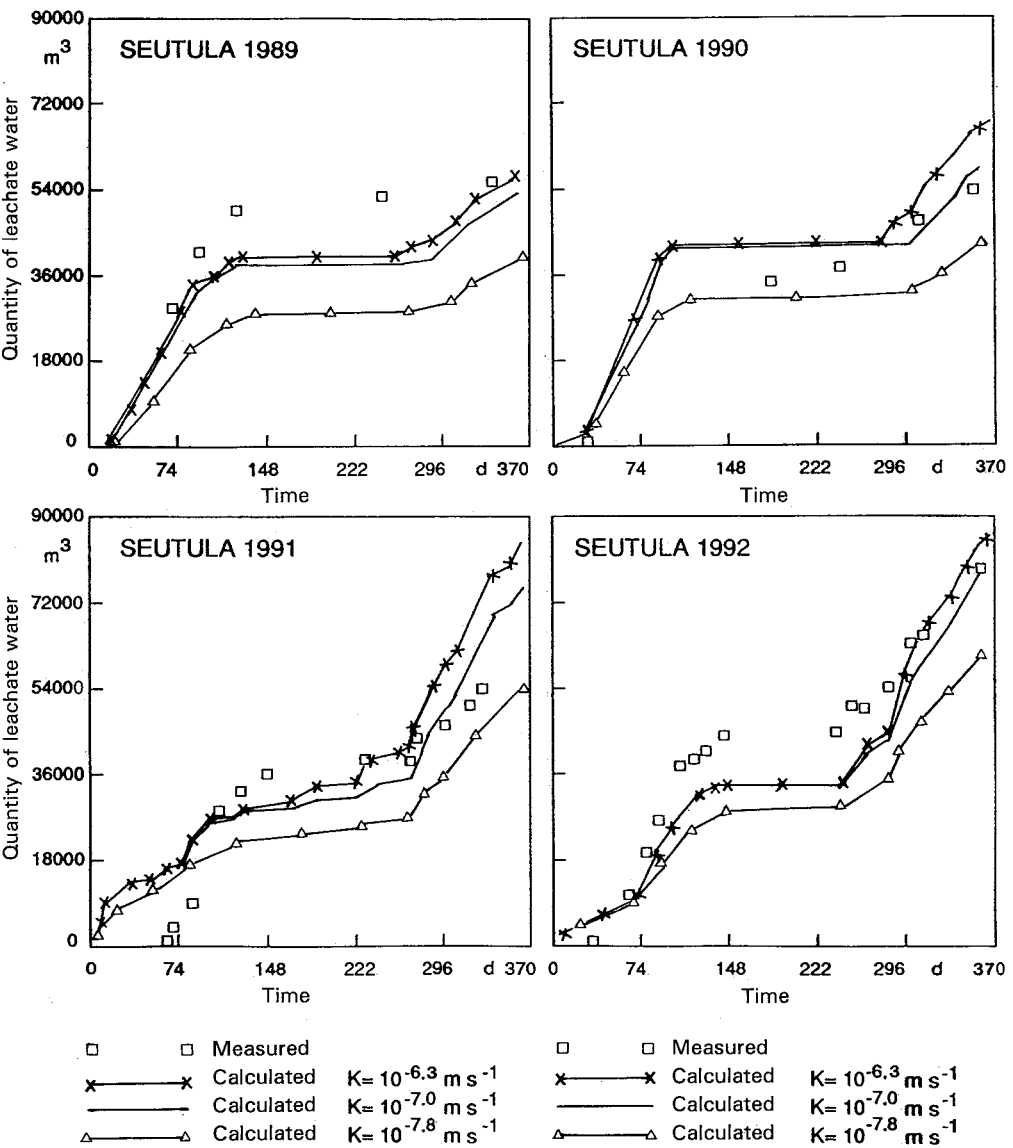
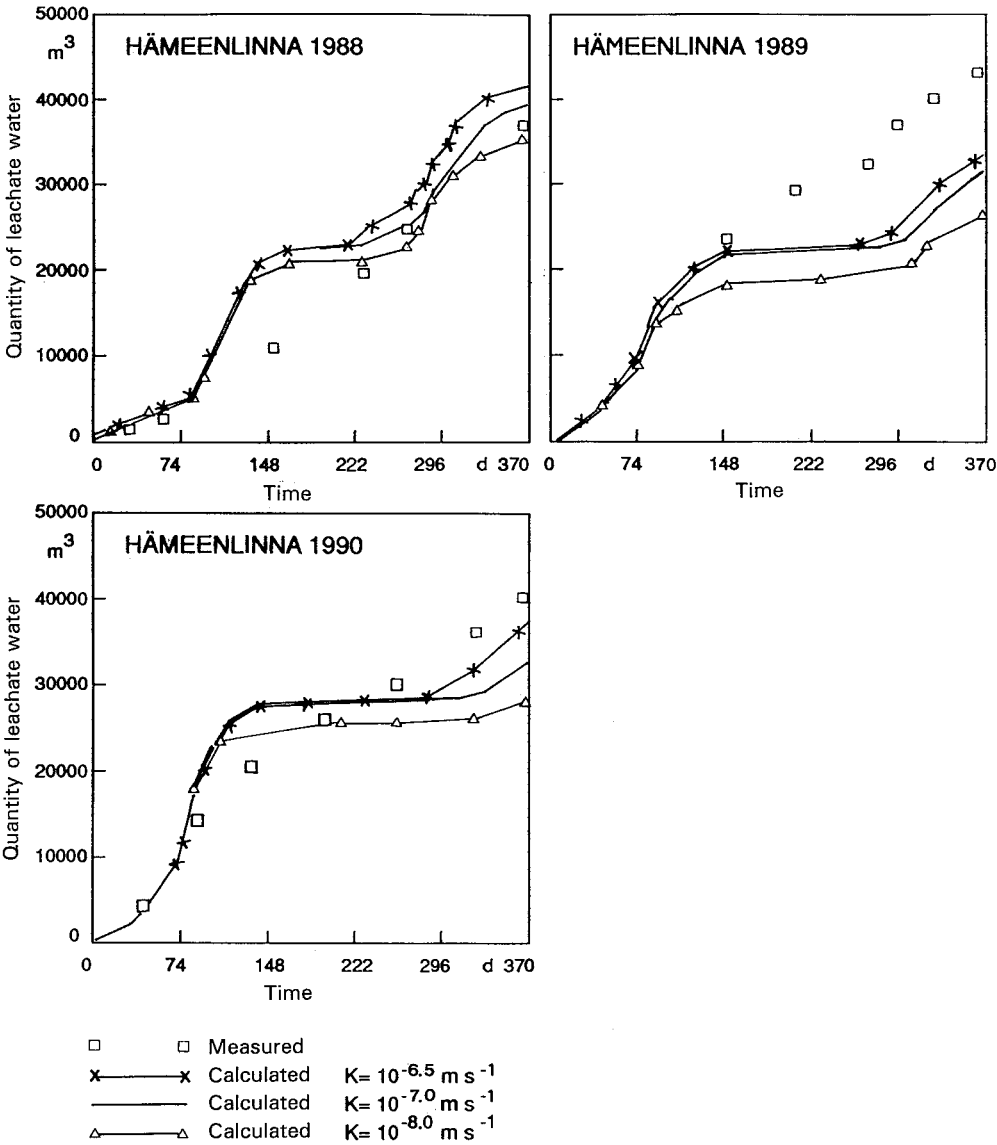


Fig. 45. The quantities of leachate waters from the Seutula landfill, actual measurements and those from LCAM in 1989–1992.



**Fig. 46.** The quantities of leachate waters from the Hämeenlinna landfill, actual measurements and those from LCAM in 1988–1990.

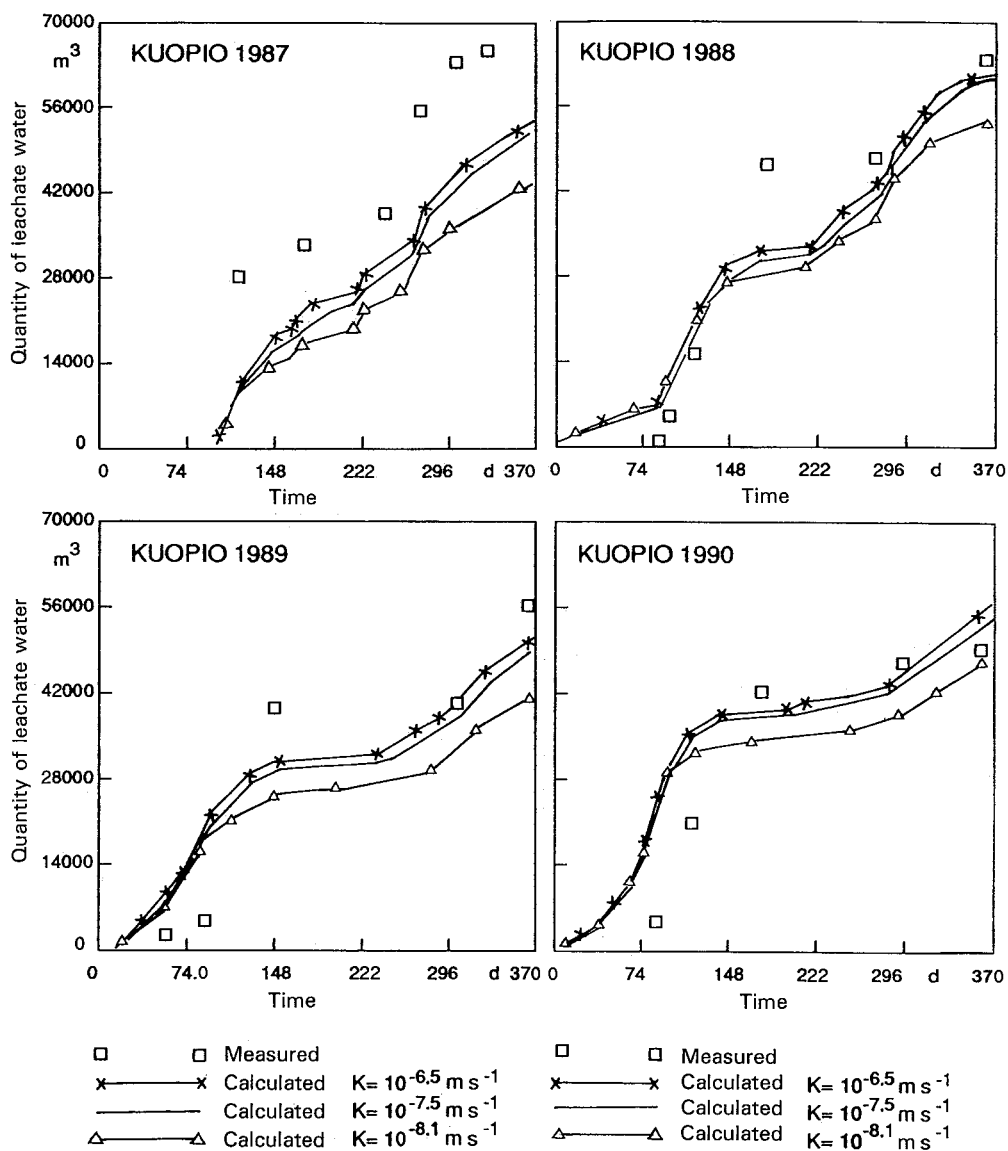
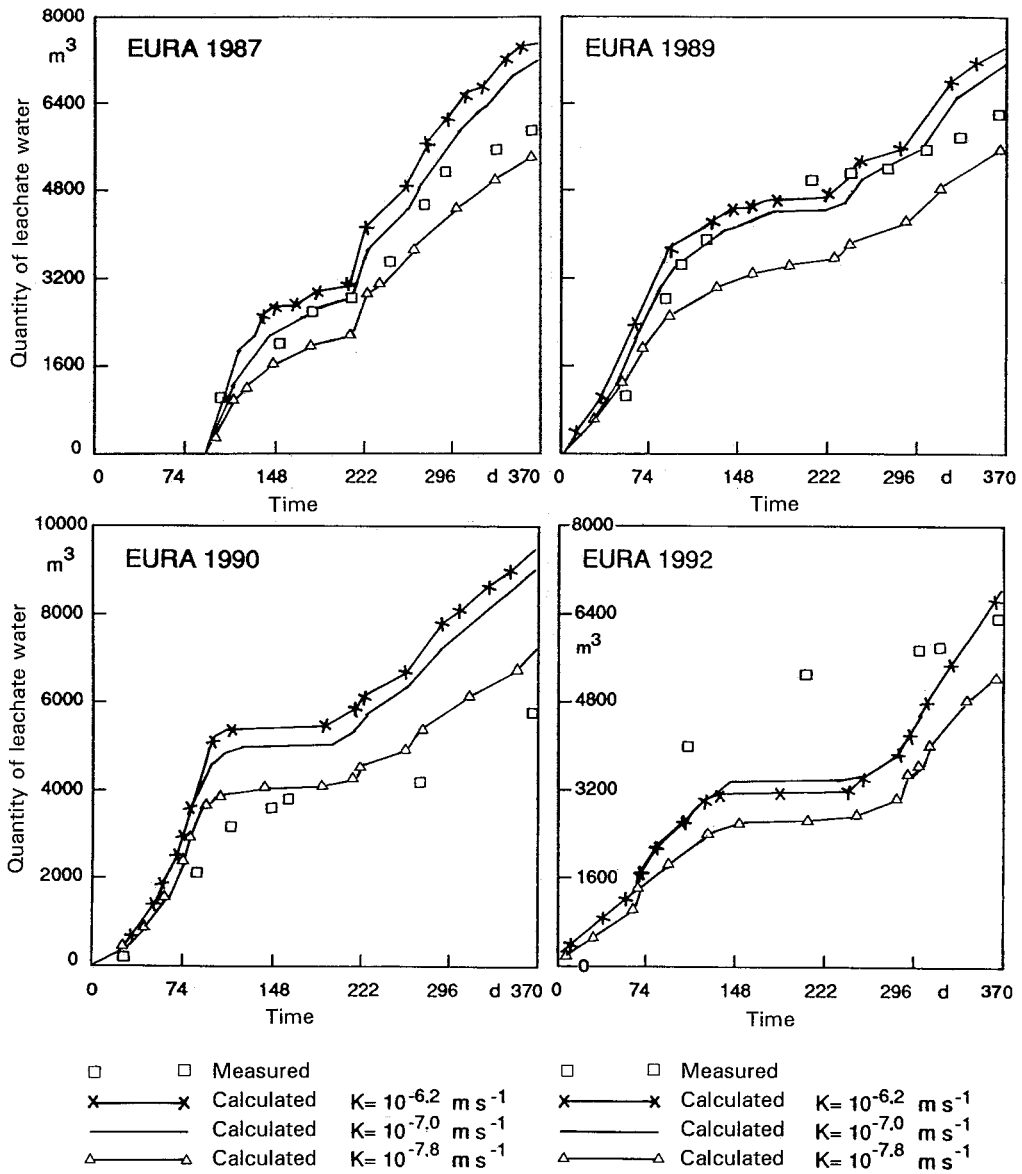


Fig. 47. The quantities of leachate waters from the Kuopio landfill, actual measurements and those from LCAM in 1987–1990.





**Fig. 48.** The quantities of leachate waters from the Eura landfill, actual measurements and those from LCAM in 1987, 1989, 1990 and 1992.

4.4.5 Results from the testing of LCAM

Seutula landfill

In the Seutula landfill the quantities of leachate waters calculated by LCAM had an error limit of 20 % compared to the measured values. With the two greatest hydraulic conductivities ( $10^{-6.3} \text{ m s}^{-1}$  and  $10^{-7.0} \text{ m s}^{-1}$ ), the calculated leachate waters differed very little from each other. It is due to the fact that with such large hydraulic conductivities the greatest part of the precipitation and melting waters infiltrated into the wastes (Fig. 45).

Hämeenlinna landfill

In Hämeenlinna the quantities of leachate waters in the years 1988 and 1990, calculated by LCAM, had an error limit of 10 % compared to the measured values. In 1989 the measured leachate waters were considerably greater than those calculated by the model. The reason for that could be the spring below the landfill or the precipitation being measured in Hattula. The distance between Hattula and the landfill was about 20 km (Fig. 46).

Kuopio landfill

In Kuopio the quantities of leachate waters calculated by LCAM had an error limit of 20 % compared to the measured values, with the exception of 1987 when the measured leachate waters were clearly greater than those calculated. No clear rea-

son for this could be given. Part of the reason might be that the precipitation was measured at Kuopio airport which is about 10 km from the landfill (Fig. 47).

Eura landfill

In the Eura landfill the quantities of calculated leachate waters had an error limit of 20 % compared to the measured values with the exception of 1990. In 1990, LCAM clearly predicted greater leachate waters than the measurements. The precipitation has been measured in Peipohja which is about 20 km from the landfill. Some of the differences could be explained by errors in the measurement of the precipitation (Fig. 48).

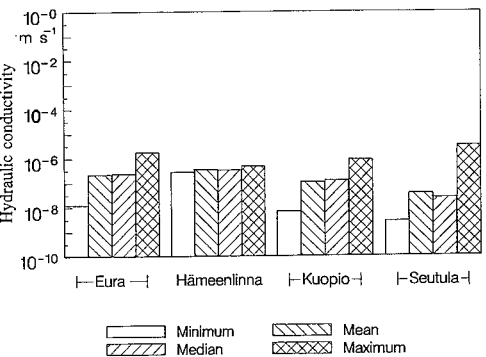


Fig. 43. Means, medians, maximum and minimum hydraulic conductivities of the surface parts of the test landfills.

Table 9. Simulation periods, annual quantities of leachate waters and hydraulic conductivities used in the simulation of LCAM.

Landfill	Testing periods	Quantity of annual measured leachate waters <sup>1) 2)</sup>		Hydraulic conductivities used in the simulation <sup>3)</sup>
		m <sup>3</sup>	mm	m s <sup>-1</sup>
Seutula	1989–1992	54 000–81 000	330–490	$10^{-6.3}$ $10^{-7.0}$ $10^{-7.8}$
Karanoja/ Hämeenlinna	1988–1990	35 000–42 000	440–520	$10^{-6.5}$ $10^{-7.0}$ $10^{-8.0}$
Silmäsuu/ Kuopio	1987–1990	48 000–64 000	400–530	$10^{-6.5}$ $10^{-7.5}$ $10^{-8.1}$
Kyöpelä/ Eura	1987, 1989, 1990, 1992	5 600– 6 300	430–485	$10^{-6.2}$ $10^{-7.0}$ $10^{-7.8}$

1) annual quantities of leachate waters are shown in Figs 45, 46, 47, 48  
2) values also include surface runoff and surface layer runoff  
3) values are based on the laboratory investigations of the samples shown in Table 8

#### 4.4.6 Relation between the infiltration and the surface runoff

The results included the total quantity of leachate waters (infiltration, surface runoff and subsurface runoff), because under the test circumstances it was impossible to measure separately the infiltration, surface runoff and subsurface runoff. It can be supposed that the surface runoff of the test landfills was small due to cracks and displacements on the surfaces of the landfills. This is due to the fact that the test landfills had not properly planned and constructed surface structures because at that time it was common practice to operate landfills without structural and vegetation quality standards.

Also according to Ettala (1987a), surface runoff is small on Finnish landfills due to the low intensity of rainfall, small landfills and displacements and cracks on surface layers of the landfills.

#### 4.4.7 Reliability of LCAM

As a result of the testing it can be seen that LCAM functioned reliably at the test landfills with some exceptions (Hämeenlinna in 1989, Kuopio in 1987 and Eura in 1990). However, in future it is worthwhile to monitor the results obtained by LCAM. It would be also useful to continue testing LCAM under more controlled circumstances where the infiltration, the surface runoff and subsurface layer runoff can be measured separately, because in these test circumstances that was impossible.

Some of the inaccuracies were due to the errors in the measurements of leachate waters and the distances between the hydrological stations and the landfills. The hydraulic conductivities of the surface parts may also be erroneous, though many samples were taken from different parts and from different depths. In the use of LCAM, one should pay special attention to the accuracy of the measurements, among other things, to the measurements of precipitation. Precipitation should be measured at the landfill because, for example, the quantities of summer rains can differ very much over even short distances.

### 5 Simulation of different factors in the approximation of the surface structures of the landfills with LCAM

#### 5.1 Background

This chapter deals with the simulation of the effects of different factors with LCAM in the approximation of surface structures e.g. the thickness and the hydraulic conductivity of the hydraulic barrier, the hydraulic conductivity and the thickness of the surface (vegetation) layer, vegetation, snow removal and a drainage layer on the quantity of the infiltration of the precipitation into the wastes.

#### 5.2 Input data and the structures analysed

In the first stage of the simulation, the aim was to find the variables which affect the quantity of infiltration into the wastes. In this stage all variables of LCAM were checked and the hydraulic conductivity of the hydraulic barrier or the surface soil layer was found to be the most important variable. On the basis of this, the simulation was carried out in such a way that the hydraulic conductivity of the hydraulic barrier or the surface soil layer varied from  $10^{-5}$  to  $s^{-1}$  to  $10^{-9} m s^{-1}$ .

In the second stage of the simulation, only the surface soil layer was examined. The thickness of the surface soil layer varied in the calculations between 100–1 100 mm and the hydraulic conductivity varied from  $10^{-5}$  to  $10^{-9} m s^{-1}$ .

In the third stage of the simulation, different methods to reduce the quantity of the infiltration to the wastes were examined e.g. vegetation, snow removal and drainage structures with the different values of the hydraulic conductivity of the hydraulic barrier.

The simulations were done at the latitudes of Helsinki, Kuopio and Sodankylä. Hydrological data was the medium values from the year 1973 to the year 1981. The medium precipitation was in Helsinki 679 mm  $a^{-1}$ , in Kuopio 667 mm  $a^{-1}$  and in Sodankylä 497 mm  $a^{-1}$ .

The slope of the landfill in the simulation was 5 %, the length of the slope 80 m, the thickness of the hydraulic barrier was 500 mm and the hydraulic conductivity was  $10^{-5}$ – $10^{-9} m s^{-1}$ , the thickness of the surface (vegetation) layer was 600 mm and

the hydraulic conductivity was  $10^{-5} \text{ m s}^{-1}$ , the thickness of the drainage layer was 200 and 400 mm and its hydraulic conductivity was  $10^{-4} \text{ m s}^{-1}$ . Fig. 49 shows surface structures used in the simulation and App. 3 shows the values of input data.

## 5.3 Effects of different factors

### 5.3.1 Effects of the surface soil layer

The simulation was begun by simulating the effects of the hydraulic conductivity and the thickness of the surface soil layer on the quantity of the infiltration into the wastes. From the results it was seen clearly that the hydraulic conductivity of the structure was the most decisive factor how much precipitation infiltrated into the wastes. According to LCAM a great decrease in the quantity of infiltration to the wastes was not attained by only increasing the thickness of the surface soil layer.

If the hydraulic conductivity of the soil layer in the simulation was  $10^{-9} \text{ m s}^{-1}$ , it was practically impervious. However, frost and settlements can increase it in practice. When the hydraulic conductivity of the soil layer was  $10^{-8} \text{ m s}^{-1}$ , about 20 % of the annual precipitation infiltrated into the wastes. When the hydraulic conductivity of the soil layer was  $10^{-5}$ – $10^{-7} \text{ m s}^{-1}$ , about 60–80 % of the annual precipitation infiltrated into the wastes (Fig. 50 a, b, c).

The differences in the quantity of infiltration between Helsinki, Kuopio and Sodankylä were due to the fact that the greater part of the annual precipitation comes in the northern parts of Finland as snow, which decreases the evaporation and increases the infiltration into the wastes. The minimum thickness of the hydraulic barrier should be about 500 mm due to cracks, settlements and constructional reasons.

### 5.3.2 Effects of the vegetation

Evapotranspiration depends greatly on the quality of vegetation, nutrient content, and thickness of the surface (vegetation) layer. The nutrient content of the vegetation layer should be checked by nutrient analyses and nutrient additions depend on the planned vegetation. The thickness of the vegetation layer must be great enough so that the vegetation has enough room for roots. Chapter 2.4.8 deals with the factors affecting the success of veg-

etation and landscaping of landfills. For example, with the blending of tree bark and sewage sludge good results have been attained with a willow plantation.

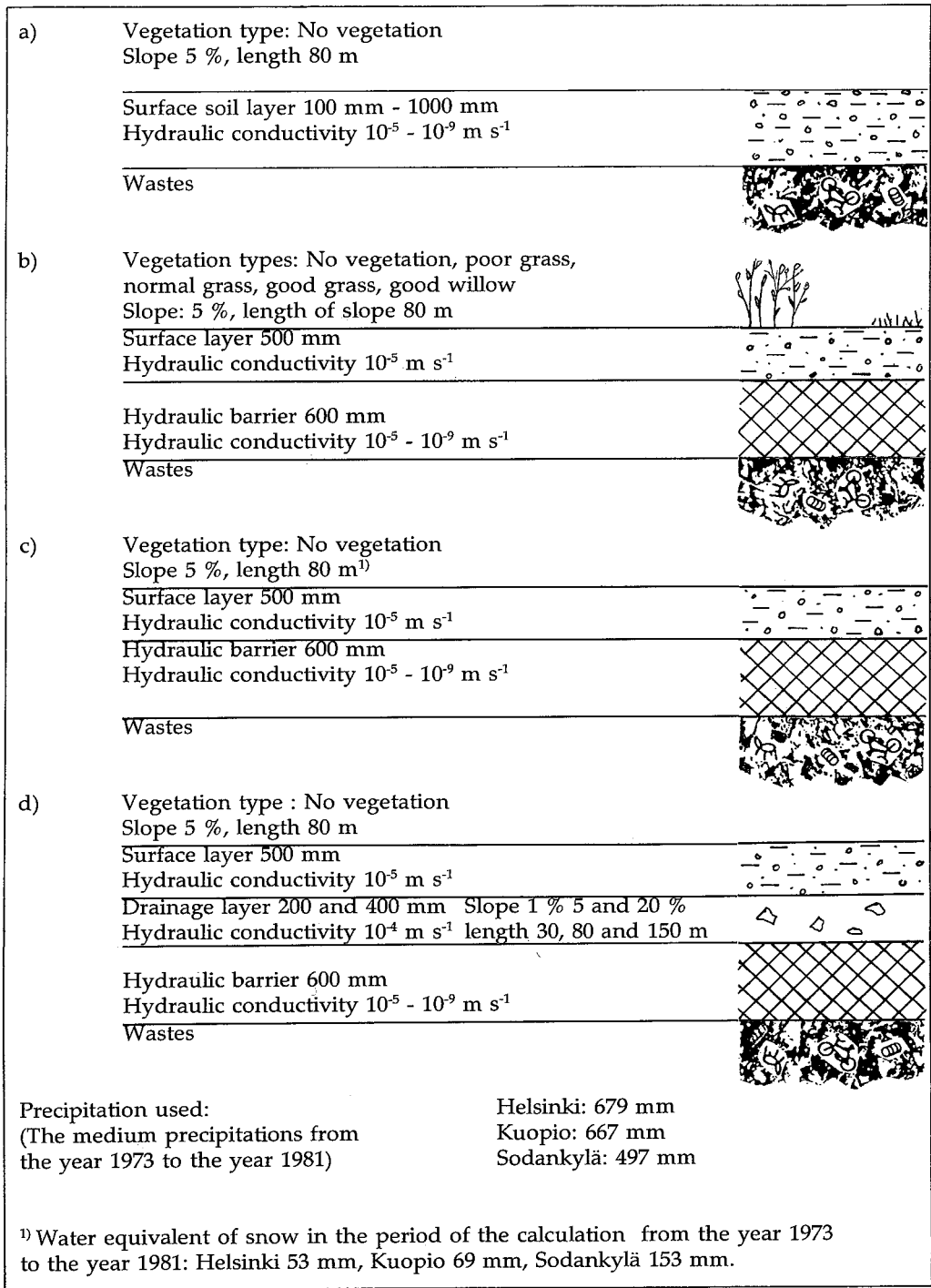
The length of the roots of the vegetation have a meaning on the thickness of the surface layer. If a too thin vegetation layer is used, it will not store enough water and then the vegetation has not enough water and the effects of evaporation and interception weaken. According to Neumann (1984), the minimum thickness of the needed vegetation layer for trees is 150 cm, 50 cm for bushes and 30 cm for grass. The rooting zone of trees must not be compacted and the surface layer must be spread with light machines. The compaction of the rooting zone is one of the greatest dangers in the success of trees on landfills.

According to LCAM, the effect of evapotranspiration, at best, was in reducing in filtration when the hydraulic conductivity was about  $10^{-7} \text{ m s}^{-1}$  or more. Then, good willow reduced about 20–30 %, good grass about 15–20 % and poor grass about 5–10 % of annual precipitation (Fig. 51 a, b, c).

### 5.3.3 Effects of the snow removal

Infiltration can be reduced by removing snow to outside the surrounding ditch of the landfill. This should happen once in the winter at the optimum time when the amount of snow is at a maximum before it starts melting. According to LCAM snow removal had the greatest effect when the hydraulic conductivity of the hydraulic barrier was about  $10^{-7} \text{ m s}^{-1}$  or more. On the latitude of Helsinki, according to LCAM, snow removal reduced the infiltration calculated with the data used in the simulation, by about 5–10 %, in Kuopio about 10–15% and in Sodankylä about 20–25 % of the annual precipitation (Fig. 52 a, b, c).

The optimum time for removing snow, according to LCAM, in Helsinki and Kuopio was the first half of March and in Sodankylä the first half of April (Fig. 54). In the simulation, the thickness of snow in Helsinki was 21.1 cm (water equivalent of snow 53 mm), in Kuopio, 27.7 cm (water equivalent of snow 69 mm) and in Sodankylä 54 cm (water equivalent of snow 153 mm). It was supposed in the simulation that a 5 cm snow cover remained on the surface of the landfill after snow removal. The infiltration was calculated from the annual precipitation. The period of the calculation was



**Fig. 49.** Surface structures in the simulation of the different factors by LCAM: effects of the surface soil layer (a), effects of the vegetation (b), effects of snow removal (c) and effects of the drainage layer (d). Other input data are shown in App. 3.

from the year 1973 to the year 1981.

It must be noted that the water equivalent of snow in the period of the calculation was low. For example the average maximum water equivalent of snow between 1961–1975 was 100 mm in Helsinki, 160 mm in Kuopio and 180 mm in Sodankylä.

However, snow removal depends often on local circumstances because, for example, landfills can be situated at high locations and then wind can blow snow away. It is also possible to take snow into consideration in the frost protection of the hydraulic barrier.

### 5.3.4 Effects of the drainage layer

The drainage layer is used in the multilayered structures. It leads part of infiltration away before it infiltrates into the hydraulic barrier. According to LCAM the effect of the drainage layer was at its best when the hydraulic conductivity of the hydraulic barrier was, on average, between  $10^{-7.5}$  and  $10^{-6.5} \text{ m s}^{-1}$ . Then it reduced the infiltration to the wastes by about 10–15 %, its thickness being 200 mm, length 80 m, slope 5 % and hydraulic conductivity  $10^{-4} \text{ m s}^{-1}$ . If the thickness was 400 mm, it reduced the infiltration by about 20–25 % of the annual precipitation (Fig. 53a).

If the drainage layer was shorter, for example, 30 m, it reduced the infiltration by about 25 %. If the drainage layer was longer, for example, 150 m, it reduced the infiltration by about 10 % (Fig. 53b).

If the slope of the drainage layer was 20 % it reduced the infiltration by about 20 %. If the slope of the drainage layer was 1 %, it reduced the infiltration by about 5 % (Fig. 53c).

### 5.4 Costs comparison of different factors

According to the above simulations with vegetation, snow removal and the drainage layer, it was possible to attain, on average, a reduction of 10–25 % of the infiltration of the annual precipitation depending on the structures and the location of the landfill. According to the construction costs (Viatek Tapiola Oy 1991), the construction of the drainage layer costs 310 000 FIM/hectare. The costs of vegetation depend very much on the type of vegetation: the planting of trees costs 200 000 FIM/hectare and light grass costs 20 000 FIM/hectare. Snow removal costs 5 000 FIM/hectare yearly.

In the cost comparison it was seen that snow removal is by far the cheapest way to reduce infiltra-

tion. Its disadvantage is, however, that it must be done yearly. However, it is possible that the cost is included in the operational costs of the landfill. If the leachate water is lead away and treated in a treatment plant, snow removal reduces the quantity of the leachate water and the costs of the treatment. In the Finnish climate, snow removal can be taken into consideration as one cheap way for the management of landfills to reduce infiltration into the wastes.

When permeable excess soil is used in the hydraulic barrier, it is possible to reduce hydraulic conductivity by adding bentonite to it. The costs of soil improved with bentonite vary from 180 000–380 000 FIM/hectare depending on the desired level of hydraulic conductivity. The quantity of bentonite varies by 1–7 % depending on the desired level of the hydraulic conductivity (Table 10).

**Table 10.** Costs of improvement of soil with bentonite (Luotojärvi, T. 1993, personal communication, Lohja Rudus Environmental Technology Oy Ab).

Hydraulic conductivity of soil needing improvement $\text{m s}^{-1}$	Hydraulic conductivity of soil improved by bentonite $\text{m s}^{-1}$	Costs	Costs/hectare; layer depth 20 cm
		FIM $\text{m}^{-3}$	FIM/hectare
$10^{-5}$	$10^{-7}$	90	180 000
$10^{-5}$	$10^{-8}$	135	270 000
$10^{-5}$	$10^{-9}$	190	380 000

### 5.5 Estimation of the surface structures chosen for covering Finnish landfills using the results of the simulation by LCAM

#### 5.5.1 Background

In this chapter, the results of simulations are used in the estimation of the surface structures chosen for Finnish landfills. The chosen types of landfill surface structures can be divided into two groups. Types 1, 2 and 3 are multilayered structures having three structure layers (hydraulic barrier, drainage layer and vegetation layer) analysed by LCAM. Types 4 and 5 are simple structures, having two structure layers (dense soil layer and surface layer) analysed by LCAM (Table 11).

**Table 11.** Surface structure layers of landfills chosen for Finnish landfills.

Structure layer	Surface structure type (Fig. 11)				
	1	2	3	4	5
Vegetation layer	x	x	x		
Surface layer				x	
Drainage layer	x	x	x		
Hydraulic barrier	x	x	x		
Dense soil layer				x	x
Gas control layer	x	x	x		
Foundation layer	x	x	x	x	x

Gas control and foundation layers were not simulated because it was supposed that they were so pervious and did not have a great effect on the quantity of infiltration. However, for example, a foundation layer can be simulated as a part of the hydraulic barrier if needed.

According to the simulations, the hydraulic conductivity of the hydraulic barrier in the types 1, 2 and 3 and the dense soil layer in the types 4 and 5 were the decisive factors in the prevention of infiltration into wastes. When a permeable material is used in the surface structures it is, however, possible to reduce the quantity of infiltration by use of vegetation, snow removal and a drainage layer.

### 5.5.2 Relations between the hydraulic barrier, vegetation, drainage layer and snow removal

Figure 50 shows that the hydraulic conductivity of the structure is the most important factor in the prevention of the infiltration of the precipitation into the waste. It also shows that, according to LCAM, an increase in the thickness of the structure does not greatly decrease the quantity of the infiltration to the wastes.

If the hydraulic conductivity of the hydraulic barrier or the dense soil layer is  $10^{-9} \text{ m s}^{-1}$  the structure is practically impervious, if there are no cracks. For example, according to Loukola

(1985b), the hydraulic conductivity of clay from Taasia is about  $10^{-10}$ – $10^{-9} \text{ m s}^{-1}$ .

When the hydraulic conductivity of the hydraulic barrier or the dense soil layer is  $10^{-8} \text{ m s}^{-1}$ , the infiltration is about 20 % of annual precipitation, if there are no cracks or settlements etc. With a good cover of vegetation this amount of infiltration can be reduced by about 5 % (Fig. 51).

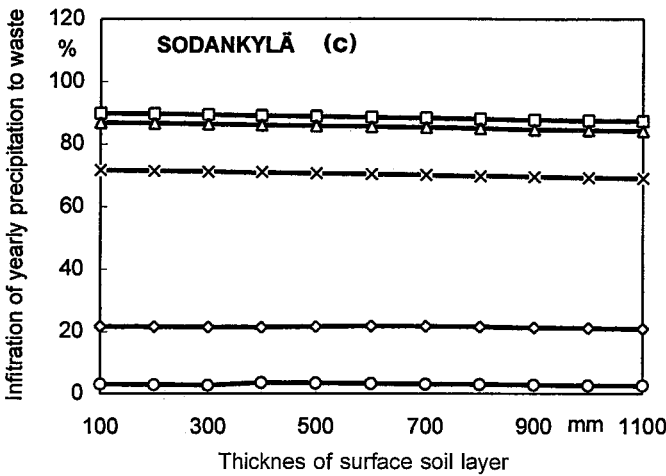
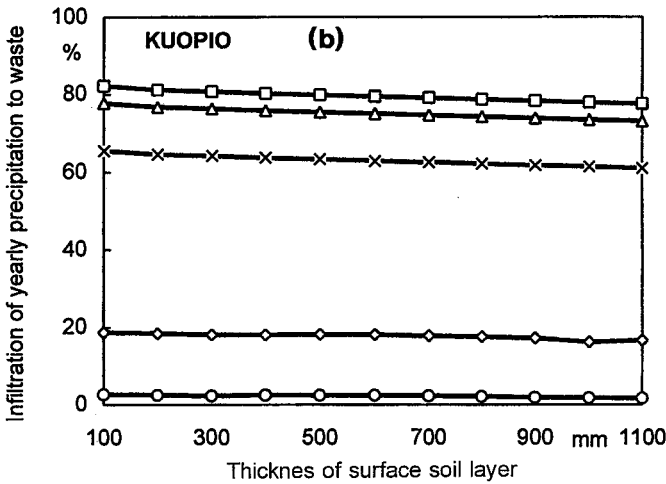
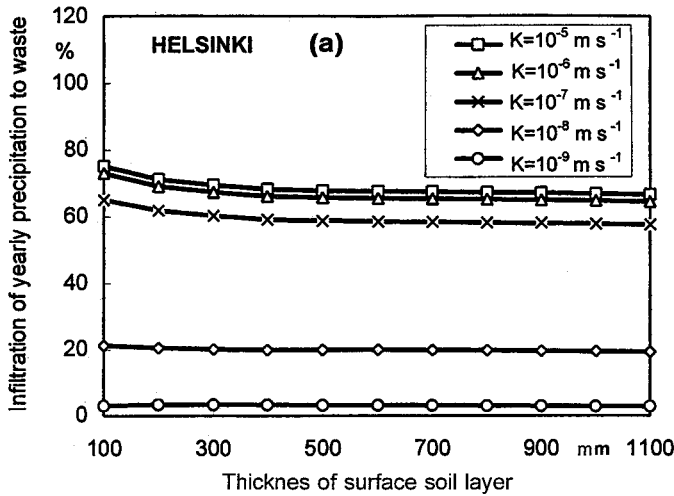
If the drainage layer is used, it can reduce infiltration for this hydraulic conductivity of the hydraulic barrier, on average, by about 10–20 %, depending on its thickness, slope and length (Fig. 53).

When the hydraulic conductivity of the hydraulic barrier or the dense soil layer is  $10^{-7}$ – $10^{-5} \text{ m s}^{-1}$ , infiltration into the wastes is about 60–80 % of the annual precipitation. For example, according to Loukola (1985b), the hydraulic conductivity of moraines in the Hautaperä, Kalajärvi and Kyrkösjärvi dams is between  $10^{-8}$  and  $10^{-7} \text{ m s}^{-1}$ . If the hydraulic conductivity of the hydraulic barrier or the dense soil layer exceeds the value of  $10^{-7} \text{ m s}^{-1}$ , a denser material should be found, or reduce the hydraulic conductivity with bentonite, geomembranes or geosynthetic clay liners. Also vegetation, snow removal or a drainage layer can be used to reduce the quantity of infiltration.

At its best, the effect of evapotranspiration from vegetation is to reduce infiltration when the hydraulic conductivity of the hydraulic barrier or the dense soil layer is about  $10^{-7} \text{ m s}^{-1}$  or more. Then good growing willow can reduce about 20–30 %, good growing grass about 15–20 % and poor growing grass about 5–10 % of the annual precipitation (Fig. 51).

The effect of snow removal is at its best when the hydraulic conductivity of the hydraulic barrier or the dense soil layer is about  $10^{-7} \text{ m s}^{-1}$  or more. At the latitude of Helsinki, snow removal can reduce infiltration by about 5–10 %, in Kuopio about 10–15 % and in Sodankylä about 20–25 % of the annual precipitation (Fig. 52). However, it must be noted that the infiltration depends on the water equivalent of snow and in the period of the calculation of this research (1973–1981) it was low.

A drainage layer is used in the multilayered structures. It leads away part of the infiltration before it infiltrates into the hydraulic barrier. The effect of the drainage layer is at its best when the hydraulic conductivity of the hydraulic barrier is, on average, between  $10^{-6.5}$  and  $10^{-7.5} \text{ m s}^{-1}$ . Then it can reduce the infiltration by about 10–25 % of an



**Fig. 50.** Effects of the hydraulic conductivity and the thickness of the soil layer on the quantity of infiltration into waste at the Helsinki latitude (a) at the Kuopio latitude (b) and at the Sodankylä latitude (c). No vegetation is on the surface of the landfill, length of the slope is 80 m and slope is 5 %. Infiltration is calculated from the annual precipitation. The surface structure and other input data are shown in Fig. 49 and in App. 3.



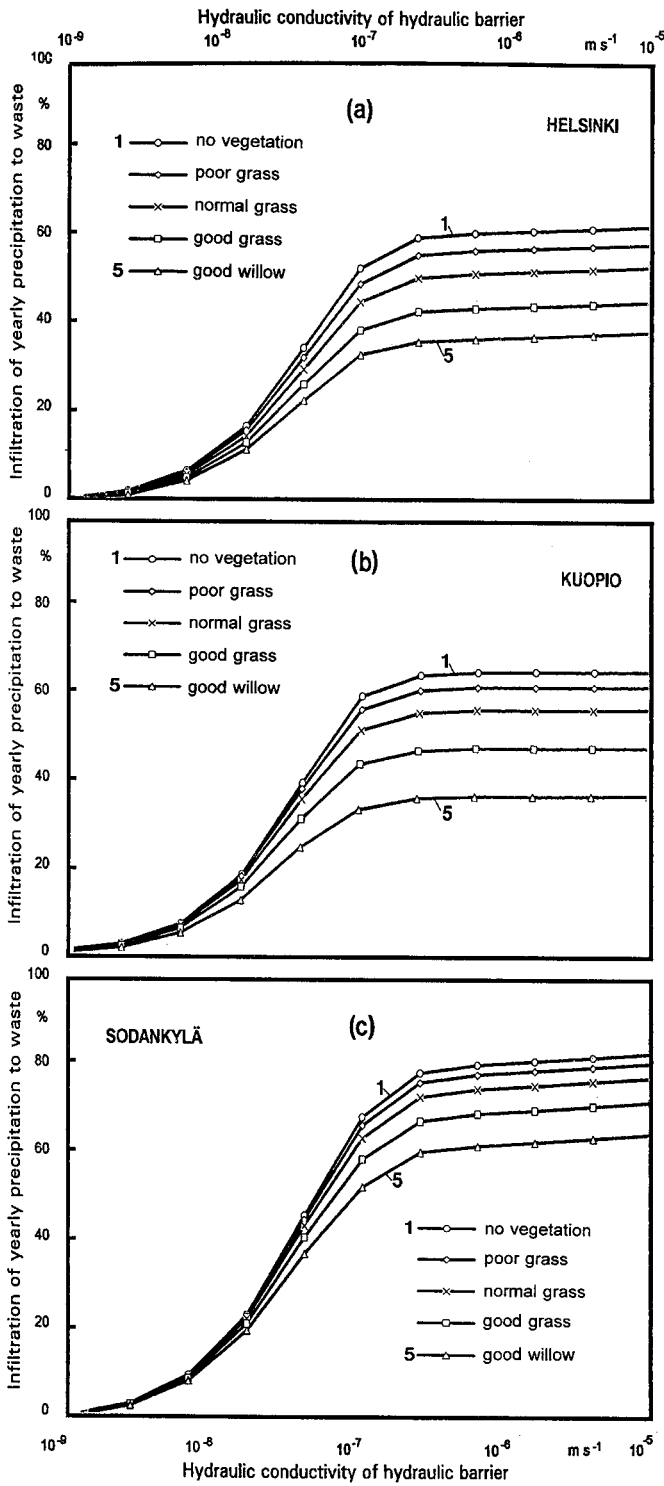


Fig. 51. Effects of the hydraulic conductivity of the hydraulic barrier and the different vegetation on the quantity of the infiltration into waste at the Helsinki latitude, (a) at the Kuopio latitude (b) and at the Sodankylä latitude (c). Length of the slope is 80 m, slope is 5 %, thickness of the surface layer is 500 mm, hydraulic conductivity is  $10^{-5} \text{ m s}^{-1}$  and the thickness of the hydraulic barrier is 600 mm. Infiltration is calculated from the annual precipitation. The surface structure and other input data are shown in Fig. 49 and App. 3.

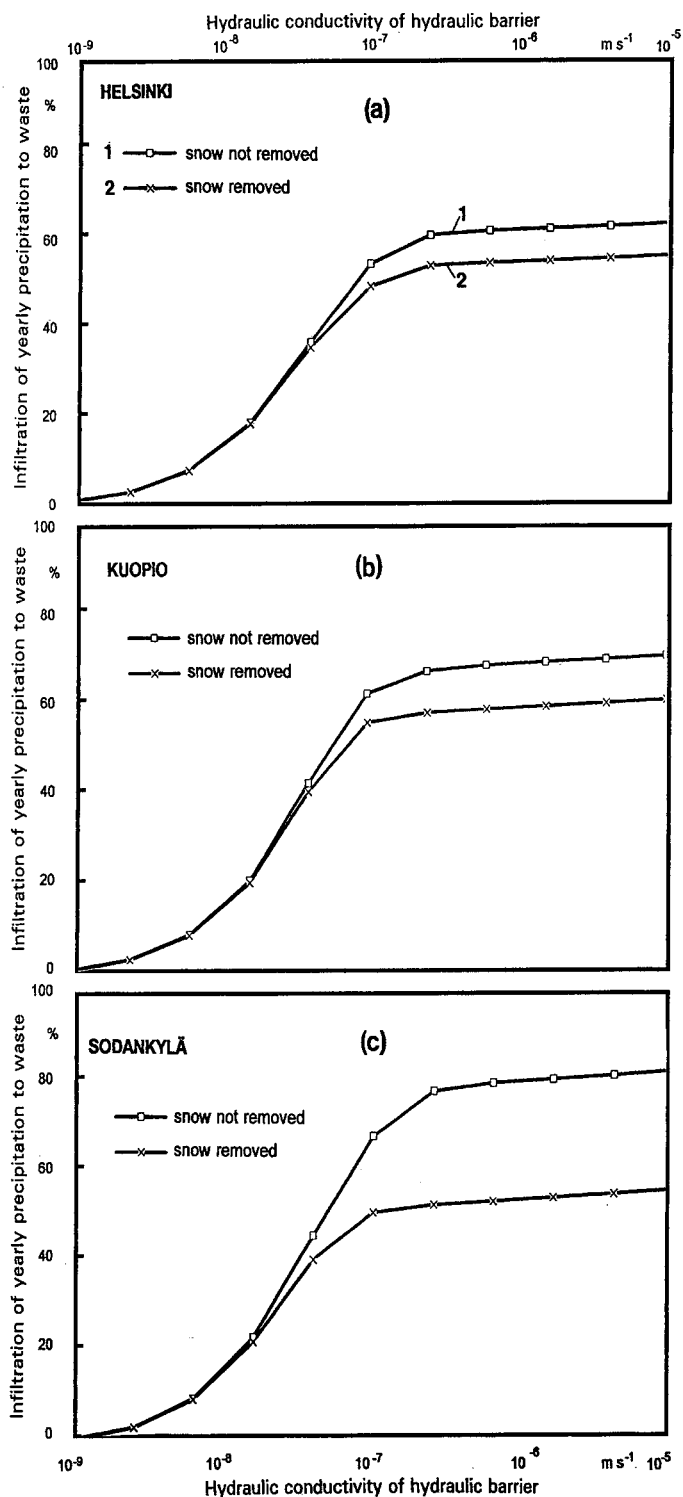


Fig. 52. Effects of the hydraulic conductivity of the hydraulic barrier and the removal of snow on the quantity of infiltration into waste at the Helsinki latitude, (a) at the latitude of Kuopio (b) and at the latitude of Sodankylä (c). No vegetation is on the surface. Infiltration is calculated from the annual precipitation. The surface structure and other input data are shown in Fig. 49 and App. 3. Water equivalent of snow in the period of the calculation from the year 1973 to the year 1981 was low, being in Helsinki 53 mm in Kuopio 69 mm and in Sodankylä 153 mm. For example, the average maximum water equivalent of snow from the year 1961 to the year 1975 in Helsinki was 100 mm, in Kuopio 160 mm and in Sodankylä 180 mm.

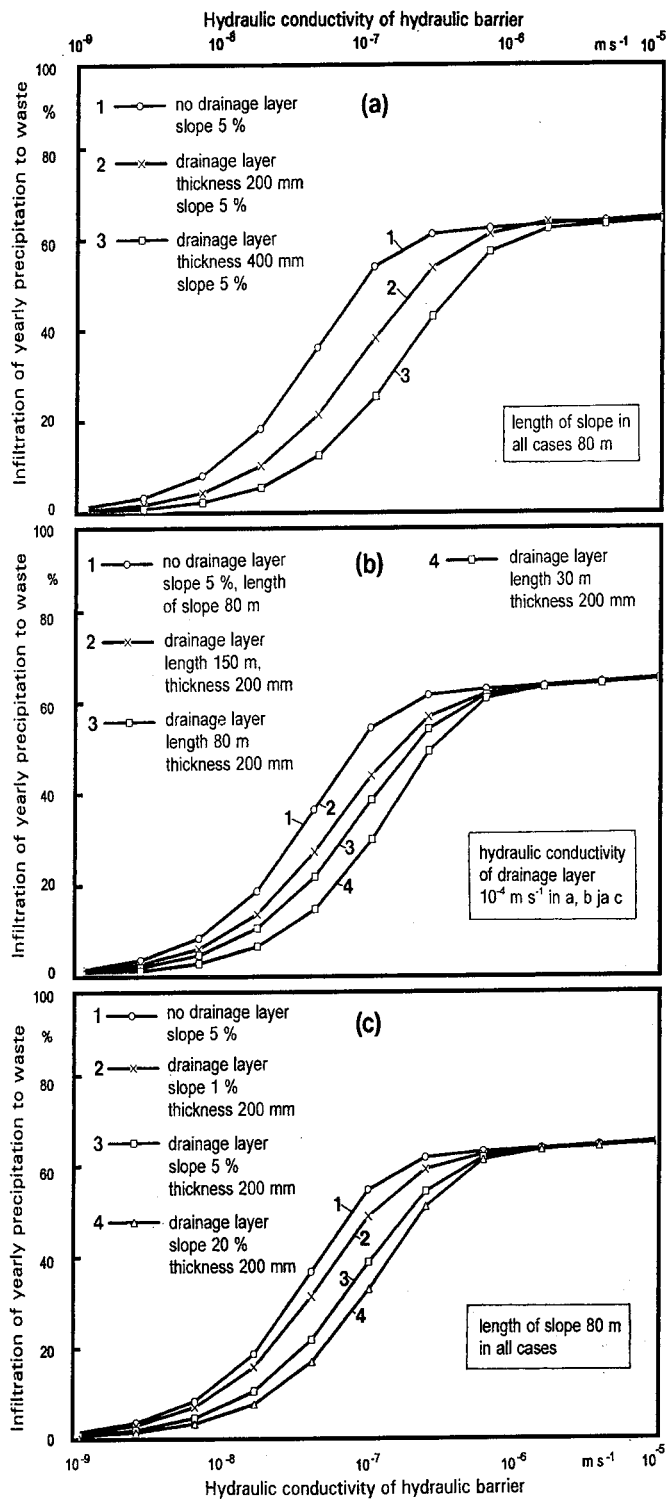


Fig. 53. Effects of the hydraulic conductivity of the hydraulic barrier and the thickness of the drainage layer on the quantity of infiltration into waste (a), effects of the hydraulic conductivity of the hydraulic barrier and the length of the drainage layer on the quantity of infiltration into waste (b) and effects of the hydraulic conductivity of the hydraulic barrier and the slope of the drainage layer on the quantity of infiltration into waste (c) at the Helsinki latitude. No vegetation is on the surface. Infiltration is calculated from the annual precipitation. The surface structure and other input data are shown in Fig. 49 and App. 3.

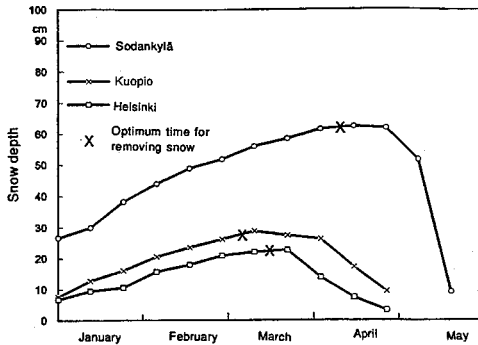


Fig. 54. Optimum time for snow removal at the Helsinki, Kuopio and Sodankylä latitudes according to LCAM. Period of the calculation is from the year 1973 to the year 1981.

nual precipitation depending on its thickness, hydraulic conductivity, length and slope (Fig. 53).

The effect of the landfill slope in preventing infiltration by increasing the surface runoff is at its greatest when the hydraulic conductivity is, on average, between  $10^{-6.5}$  and  $10^{-7.5}$   $\text{m s}^{-1}$ . Then it can reduce, for example, the infiltration about 20 % of the annual precipitation when the slope is 20 % (Fig. 53c). However, cracks and settlements often prevent surface runoff.

The chosen thicknesses of vegetation layers for different types of vegetation should be of values such as those presented by Neumann (1984). According to him, the minimum thickness of the vegetation layer for trees is 150 m, 50 cm for bushes and 30 cm for grass.

In summary, the hydraulic conductivity of the hydraulic barrier, in the types 1,2 and 3 and the dense soil layer in the types 4 and 5, is the most important factor in preventing infiltration of precipitation into waste. In practice, the material and requirements for the tightness of the hydraulic barrier must be decided on the risk assessment of the environmental consequences of the landfill (Chapter 6). The minimum thickness of the hydraulic barrier or the dense soil layer should be about 500 mm due to cracks, settlements and constructional reasons. However, it must be noted that, in practice, differential settlements, uneven compression of underlying waste and frost will almost certainly produce cracks within the hydraulic barrier and increase the hydraulic conductivity. Therefore, models, in general, are most applicable for the early period after placement but later, the leakage estimates provided by models are ex-

pected to underestimate the actual field conditions. This is also the case in LCAM developed in this research.

If infiltration caused by settlements and cracks are expected to cause a serious threat for ground- or surface waters, then the use of bentonite mixtures, geomembranes and geosynthetic clay liners must be considered because they are much better able to resist these kinds of damage than, for example, compacted clay.

## 5.6 Practical examples for the use of the results of simulation by LCAM in the approximation of infiltration into the wastefill

Design diagrams in Figs 50–54 can be used in the approximation of the quantity of the infiltration into the wastefill. In the following, some examples of their use are shown. LCAM can be used in the exact analysis.

### Example 1

Clay is used in the hydraulic barrier of a closed landfill. Its hydraulic conductivity is  $10^{-9}$   $\text{m s}^{-1}$ . The Helsinki latitude is used in the example. With this value of the hydraulic conductivity an almost impervious structure is attained, if there are no cracks and settlements caused, for example, by frost (Fig. 50a). The minimum thickness of the hydraulic barrier should be about 50 cm. A surface layer must also be on the hydraulic barrier and its thickness depends on the planned vegetation and enduse. The nutrient content of the surface layer must be checked by nutrient analysis. Vegetation is important in evapotranspiration and for the prevention of erosion and landscaping. It is possible to also build a drainage layer on the hydraulic barrier. Probably the displacement of wastes caused by organic decomposition and frost will increase the hydraulic conductivity of the hydraulic barrier.

### Example 2

Same moraine which is used in the structures of the Kyrkösjärvi dam is used in the surface structures of a landfill. Its hydraulic conductivity, according to Loukola (1985b), is about  $10^{-7.0}$   $\text{m s}^{-1}$ . The Kuopio latitude is used in the example. 65 %

of the annual precipitation infiltrates into the wastes (Fig. 50b). Good willow vegetation decreases the infiltration by about 25 % and then total infiltration into the wastes is about 40 % of the annual precipitation (Fig. 51b). If all the landfill is covered by well growing willows, snow removal is then difficult. However, if the vegetation type is good grass, it decreases the infiltration by about 15 %. Then snow removal is also possible and it can decrease infiltration by about 5% (Fig. 52b). The total infiltration to the wastes is then about 45 % of the annual precipitation.

#### Example 3

Surface structures have been designed for the industrial landfill of Outokumpu Polarit Oy (Fig. 55). The hydraulic barrier moraine layer. The thickness of the moraine layer is sufficient but its efficiency in preventing infiltration depends greatly on its hydraulic conductivity which is not shown. If its hydraulic conductivity is the same as the moraine of the Kyrkösjärvi dam (Loukola 1985b), being about  $10^{-7.0} \text{ m s}^{-1}$ , the hydraulic conductivity of the structure is too great. The hydraulic conductivity can be reduced by adding bentonite so that the hydraulic conductivity is  $10^{-9} \text{ m s}^{-1}$ . The other structures are the foundation layer, which is slag from a steel mill (thickness 500 mm). The filter layer (thickness 100–200 mm, made of ground FeCr slag) is acceptable and the surface layer (thickness 400 mm) and the slope (5%) are also acceptable. The nutrient content of the surface layer must be checked by nutrient analysis. For example, a blending of bark and sewage sludge can be used in the surface layer. Vegetation can be, for example, willows which have a good capacity of evaporation.

Frost is not, however, taken into consideration in the design of the protection of the hydraulic barrier. The frost depth in the Tornio area is about 220 cm (Suomen Rakennusinsinöörien liitto RIL ry 1988). On the surface of the hydraulic barrier there should be an extra 180 cm thick soil layer which, together with the surface layer (40 cm) in the plans, are sufficient frost protection for the hydraulic barrier.

#### Example 4

Surface structures have been designed for the landfill of the Puumala community (Fig. 56). The designed structure represents the simple cover types 4 and 5 (Fig. 11 d, e). As the landfill does

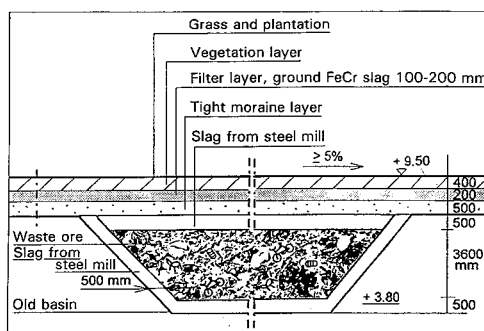


Fig. 55. Surface structures of the industrial landfill of Outokumpu Polarit Oy. (Outokumpu Oy 1988).

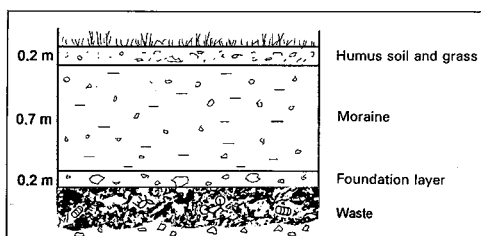


Fig. 56. Surface structures designed for the landfill of the Puumala Community (Maa ja Vesi Oy 1993).

not pose an environmental risk, according to the closing plans, the structure type and layer thickness are acceptable. The 20 cm humus layer on the surface layer is sufficient for grass and the 70 cm moraine layer under it is also sufficient. The structure also has a 20 cm foundation layer. Frost is not a necessary consideration in this type of simple structure. As methane and sulphur compounds partly oxidize in the surface layer it is useful to use a compost or other material as a biofilter in this type of small landfill, with an area of a few hectares.

#### Example 5

Figure 57 shows the surface structures of the Mankkaa landfill. Greenbuilding plans have been prepared for it. They include, for example, tree plantations. The hydraulic barrier is 50–100 cm thick clay and moraine and its thickness is sufficient. However, the plans do not include landfill gas removing structures which are important when tree plantations are on a landfill. Landfill gas removing structures secure the success of tree plantations. It is also seen that a 15–20 cm layer

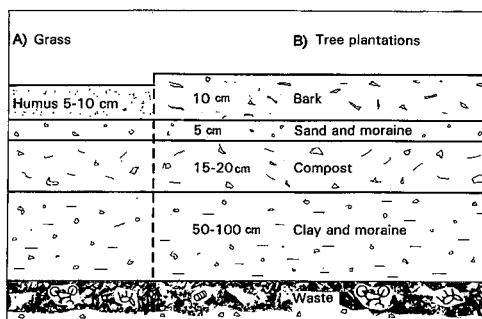


Fig. 57. Surface structures of the Mankkaa landfill in Espoo (Espoon kaupunki 1990).

of compost, sand and moraine (5 cm) and bark (10 cm) are used in the surface material of the landfill. These materials are shown as different layers. However, good growth results are attained by blending these materials. Sand and moraine reduce the specific electrical conductivity of compost and they should be mixed well before planting, for example, with agricultural machinery. The bark prevents weeds when it is spread top-most on the surface layer and in this respect it is the right amount. The thickness of the surface layer is too thin for trees (45 cm) and it should be about 150 cm.

## 6 Discussion

### 6.1 Aspects to be considered in the closing of landfills

The results of different parts of this study are combined in this chapter to produce general points to be considered in the closing of landfills. The points make the controlled reduction of the leachate waters of closed landfills possible.

The old landfills have been mostly built without proper planning for the location, the foundation, the closing and the surface structure of landfills. Newer landfills, in general, have foundation plans according to the requirements when built.

Here, only the design of surface structures is discussed. If landfills also need, for example, vertical tightening structures, then they must be designed separately. From the results of the study the aspects to be considered in the closing of landfills can be divided into nine phases (Fig. 58).

### 6.2 Phases of the closing of landfills

#### Phase 1: Risk assessment of environmental consequences for a landfill

In the first phase a risk assessment of the environmental consequences of the landfill must be done with the co-operation of environmental authorities, owners and other parties. The history of use of the landfill must be declared in it. The most important factor to be clarified is the effect of leachate waters on the ground- or surface waters. For example, modelling and earlier research results on environmental consequences of a landfill can be used in a risk assessment.

Requirements for the tightness of the surface structures of the landfill and how much infiltration into the wastes can be allowed depend on the results of the risk assessment. When the landfill is situated on the ground- or surface water area, and the risk assessment suggests that the landfill can have a harmful effect on them, the hydraulic barrier must be an impervious material. The choice of surface structure type depends greatly on the enduse of the landfill. Light structures are good for landfills which do not contain environmental risks and which are not designed for active enduse. If the landfill contains environmental risks, and it is designed for active enduse, then higher quality structures must be used.

In this phase one must also estimate if the surface structures are, in general, sufficient to reduce environmental consequences of a landfill or is there a need for further measures, for example, vertical tightening structures or changing the direction of the groundwater flow by pumping. Also, landfill mining must be considered. In the most serious case, one must even consider the removal of the whole landfill to another place when the landfill contaminates, for example, the groundwater area.

#### Phase 2. Stability, settlement, compression and frost action

In this phase the deformation qualities and stability of wastes and the foundation must be investigated. One must check, among other things, that the landfill can support, without failure, the extra weight caused by the surface structures.

If the stability is not good enough, it can be improved, for example, by lowering the slope and by moving wastes to another place.

In this phase it must also be investigated if the landfill is compacted enough or are uneven settlements a danger to the tightness of the structures. Settlements can be reduced by extra compaction. However, in spite of the development of compaction methods, settlements together with frost are, in general, the greatest danger to the tightness of surface structures.

For example, if infiltration caused by settlements and cracks are expected to cause a serious threat for ground- or surface waters, the use of bentonite mixes, geomembranes and geosynthetic clay liners must be considered because they are much better able to resist these kinds of damage than, for example, compacted clay.

Large settlements can be minimized by placing a temporary, relatively permeable cover on the waste and collecting leachate waters for several years, treating the landfill as an active bioreactor. After significant biodegradation of the waste, and after the waste mass has become relatively stable, a final, engineered cover can be placed over the waste. By stabilizing the waste prior to placement of a final cover, the probability of the cover performing as designed is maximized.

The risks of damage caused by frost to the surface structures have to be taken into consideration with proper design. Then, for example, the maximum frost depth in the location must be clarified.

The effect of the temperature of wastes on the frost depth must, if needed, be measured or calculated, because the new landfill technology aims e.g. to enlarge, centralize and increase the height of landfills and to produce more methane. It can be supposed that the temperatures of landfills are in future higher which will decrease the frost depth. For example, temperatures of landfills measured in USA have been about +40 °C and in UK about +50 °C. Differences are caused by the different composition of wastes.

If frost or settlements cause cracks to the hydraulic barrier, the hydraulic conductivity of the hydraulic barrier made of clay can increase very much. In practice, it can mean, for example, that the hydraulic conductivity can increase from the value  $10^{-9} \text{ m s}^{-1}$  to the value  $10^{-7} \text{ m s}^{-1}$ . Then according to LCAM, infiltration into the wastes can increase from about 5 % to about 60 % of annual precipitation (Fig. 50a). By covering the clay with a soil layer, which prevents its drying, and by making a drainage layer, which leads the infiltration

quickly away, it is possible to attain a very low level of infiltration.

### Phase 3: Landfill gas formation

In the third phase, landfill gas formation must be researched from the point of view of vegetation, construction and enduse. Portable methane measurement instruments can be used in the measurements of methane. The utility use of landfill gas must be researched using wider and separate studies. In planning one must take into consideration the fact that landfill gas containing methane is explosive. The disadvantages to the vegetation and the danger of explosion can be prevented by building gas removing structures or by removing wastes from under the structures.

Part of the methane and sulphur compounds oxidize in the surface layer of landfills. For this reason the use of compost or other material as a biofilter can be investigated especially on small landfills, with areas of a few hectares.

### Phase 4: Choosing the type of surface structure

In the fourth phase a suitable type of the surface structure must be chosen for the landfill. The requirement for the hydraulic conductivity of the hydraulic barrier depends on the results of the risk assessment of the landfill. Enduse effects the choice of surface structure type. Structure type 1 (Fig. 11 a) is the thickest and multilayered. Landfills containing environmental risks such as the possible contamination of groundwaters need this type of high quality, multilayered, surface structure. Also, when the aim is to take the landfill into active afteruse, one must consider building these types of multilayered surface structures (Fig. 11 b, c). Light and simple cover structures (Fig. 11 d, e) are sufficient for landfills which do not contain environmental risks and which will not have an active afteruse.

In this phase the hydraulic conductivity of the hydraulic barrier must also be researched in the laboratory and insitu. It is the most important factor influencing the quantity of infiltration into the wastes. Clay or moraine can be used in the hydraulic barrier. Their hydraulic conductivity can be reduced by adding bentonite. The drying of clay can be prevented by covering it with a soil layer.

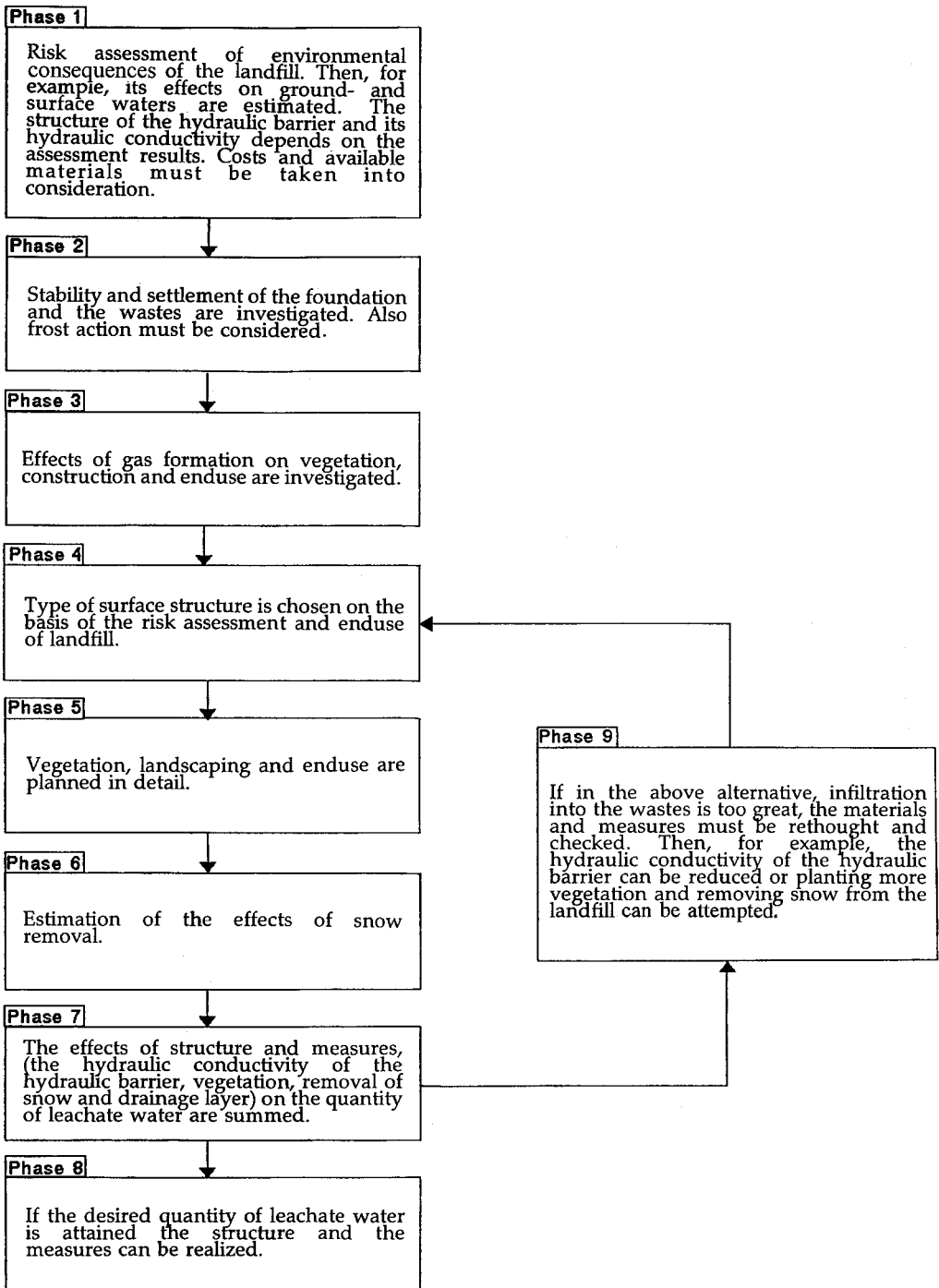


Fig. 58. Aspects to be considered in the closing of landfills.



### Phase 5: Vegetation, landscaping and enduse

In the fifth phase the vegetation, landscaping and enduse are planned in detail. Special attention must be paid to good vegetation and landscaping because they reduce infiltration with evapotranspiration and interception, and they help the landfill to merge with the surrounding environment. Excess soils brought to the landfill are, in general, not good enough for vegetation, because they are often poor in nutrients and they can contain toxic compounds. The blending of bark and sewage sludge has attained good results with willow plantations. Suitable nutrient contents can be researched with nutrient analysis for the planned vegetation. The rooting zone of the trees must not be compacted and the vegetation layer must be put down with light machines. The compaction of the rooting zone is one of the greatest dangers to the success of trees on landfills. If needed, the surface must be prepared with agricultural machines. Evaporation depends on the type of vegetation and the evaporation and interception from good willow plantations can be about 30 % of annual precipitation. The more active the enduse is on the landfill, the greater is the benefit obtained from it. In the choice of enduse, the main principle must be that the landfills near habitation are best suited for outdoor life and recreational purposes, and landfills far from habitation are best for such activities as motor sport and storage areas for industry.

### Phase 6: Snow removal

The meaning of snow removal in the water balance of landfill must be clarified. Snow removal can be recommended from the point of reducing environmental effects of landfills and it should always be done whenever possible. Snow removed from the surface of a landfill does not infiltrate when it melts but it flows away as clean water to the surrounding area. For example, in the calculation period with LCAM between 1973–1981 at the latitudes of Helsinki, the snow removal reduced infiltration about 5–10 %. On the latitude of Kuopio it reduced infiltration by about 10–15 %. In northern Finland it had a greater effect. For example at the latitude of Sodankylä it reduced infiltration about 25 % (Fig. 52).

However, it must be noted that the quantity of the infiltration depends on the water equivalent of

snow and in the calculation period of this research it was low. Snow removal depends often also on local circumstances because, for example, landfills can be situated at high locations and then wind can blow snow away. It is also possible to take snow into consideration in the frost protection of the hydraulic barrier.

### Phase 7–8: Summarized effects of structures and measures

In these phases the effects of structures and measures (hydraulic conductivity of the hydraulic barrier, vegetation, snow removal and drainage layer) are summed to see the quantity of infiltration to wastes. If the desired level for the quantity of infiltration is attained, the structure and the measures can be realized.

### Phase 9: Checking

If in the above phases the infiltration to the wastes is too great, materials and measures must be re-examined and checked. Then, for example, the hydraulic conductivity of the hydraulic barrier can be reduced, more vegetation planted and snow removal employed on the landfill.

Chapter 5.6 shows practical examples of the use of the design diagrams (Figs 50–54) simulated by LCAM in the approximation of different factors in the reduction of infiltration into the wastefill. In the exact analysis LCAM can be used.

## 6.3 Reliability of results and error estimation

In the first phase of the testing of LCAM, the heights of the water levels in the landfills were measured. According to the results, the water levels in the landfills were far from the surfaces of the landfills in all seasons. The water levels were, on average, midway between the top and the bottom of the landfills. They were about 7.5–14.0 m from the surface depending on the total height of the landfills. At the edges of the landfills, the water levels were at the level of the surrounding ditches.

This means, in practice, that after rainfall the surface layer is at once in a hydraulic state of balance and the fundamental presupposition of LCAM is right. Among other things this is due to

the way of construction of landfills in Finland where the leachate waters can spread to the surrounding ditches. Therefore in landfills there is free void for infiltration of precipitation.

In the second phase of the testing of LCAM it was shown that the components of the water balance model calculated with LCAM had very minor differences with the components calculated with the quasi 3-D model. Therefore LCAM is sufficiently accurate and it is not necessary to use the complicated quasi 3-D model. Thus, LCAM is usable in the practical approximation of surface structures. However, in future it is worthwhile to monitor the results obtained by LCAM because in this work it could be tested only in a limited scale.

In the third phase, amounts of the leachate waters calculated by LCAM were compared to the measured values in the test landfills. It must be noted that it was difficult to find landfills to test the model where leachate waters had been measured for a long enough time. The landfills were not the best from the point of view of testing because they were partly in use. They did not have a proper hydraulic barrier but they were covered by soil layers. The hydraulic conductivity of the surface soils was measured from samples in the laboratory and it was  $10^{-5.5}$ – $10^{-8.6}$  m s<sup>-1</sup>. However, the simulation was not only done with one value of the hydraulic conductivity. It was done with three different values for each landfill based on the measurements in the laboratory ( $10^{-6.3}$ – $10^{-8.1}$  m s<sup>-1</sup>), to see how sensitive LCAM was to the changes of the hydraulic conductivity.

LCAM functioned reliably apart from some exceptions (Hämeenlinna in 1989, Kuopio in 1987 and Eura in 1990). With the average value of the hydraulic conductivity ( $10^{-7}$  m s<sup>-1</sup>) and leaving the above mentioned exceptions away, the results calculated by LCAM varied about 0–20 % from the measured amount of the leachate waters.

The exceptions and error factors calculated by LCAM were due to the inaccuracies of the data concerning the surface soils and the long distances between the landfills and the hydrological stations. The greatest distance was about 20 km. This maybe, for example, caused great differences in the amounts of predicted leachate waters with summer rainfall.

The method of measurement for the leachate waters also caused uncertainty in the results. In Seutula and Kuopio it was done with water gauges,

in Hämeenlinna by the number of hours a water pump was in use and in Eura by measurements from the discharging pipe. Though the water gauge measurements were, in general, accurate, the freezing of the outer surrounding ditch and erosion failures in the leachate basin dam have caused a minor uncertainty in the results in Seutula. In Hämeenlinna the accuracy of the pump and the spring in the landfill area have caused uncertainty in the results. In Eura the heavy rains have caused uncertainty in the results.

The measurements of the leachate waters have not been done under controlled circumstances and the imprecision of the measurements have caused uncertainty in the results. Compared to the earlier research results, the quantities of leachate waters in this research were higher. Part of the differences can be explained by earlier research measurements being done under more controlled and different circumstances. A more controlled way of testing in this study would be to measure separately infiltration, surface runoff and surface layer runoff but in the testing circumstances of this study that was impossible.

Because LCAM calculated the total quantity of leachate waters, which included the infiltration, the surface runoff and subsurface layer runoff, the errors caused by input data and errors in the measurements could not be separated from the errors caused by the model. The reason for this was that there was not enough accurate data concerning hydrology, the amount of the leachate waters and the hydraulic conductivities of the surface structures.

The sensitivity of LCAM to the changes of the hydraulic conductivities was seen when one compared the amounts of leachate waters calculated with three different hydraulic conductivities. When the hydraulic conductivity of the surface structure was reduced, on average, from  $10^{-6}$  m s<sup>-1</sup> to  $10^{-8}$  m s<sup>-1</sup>, the total amount of the leachate waters, which included infiltration, surface runoff and subsurface layer runoff, was reduced, on average, by 20–30 %.

After design and building the surface structures, the greatest dangers are the settlements and cracks caused by frost, and decomposition of organic waste which increase the hydraulic conductivity. Though landfills are compacted very well, the decomposition of the organic material always causes displacements and cracks in the surface structures. None of the models mentioned in Chap-

ter 3 incorporate the potential failure of cover liners and the resulting leachate generation. As such, it is likely that the models are most applicable to the early period after placement. In later stages, the leakage estimates provided by these models are expected to underestimate the actual field condition. It is also the case in LCAM developed in this study.

In using LCAM, attention must be paid to the exactness of the measurements, among other things, to the hydrological data. The measurements of precipitation should be done at the landfills because there can be great variations in the amounts of summer rain over short distances.

It would be useful to continue the testings of LCAM under more controlled circumstances where the infiltration, surface runoff and subsurface layer runoff can be measured separately because under these test circumstances it was impossible.

## 7 Conclusions and recommendations

The following general conclusions may be drawn from this study.

- With the model developed and tested in this study the different factors in the surface structures of landfills can be approximated in Finnish conditions. However, in future it is worthwhile to monitor the results obtained by the Landfill Cover Approximation Model (LCAM) and to continue the testing in different situations because in this work it could be tested only in a limited scale. The factors which can be calculated are the thickness and the hydraulic conductivity of the hydraulic barrier, the thickness and the hydraulic conductivity of the surface layer, vegetation, snow removal and drainage layer. The testing and the simulation proved that the model does not need the pF-curve of waste as an input parameter because the hydraulic conductivity of landfill waste is, according to earlier studies, so great that the hydraulic conductivity of the hydraulic barrier is the critical factor in simulations.
- The main components which have the greatest effect on the quantity of infiltration of precipitation into the wastefill are the hydraulic conductivity of the hydraulic barrier, vegetation,

snow removal and the drainage layer. In approximations, design diagrams presented in this study can be used and in the exact analysis LCAM can be used.

- For practical purposes different aspects to be considered in the closing of landfills are also presented. On the grounds of the study, this makes the controlled reduction of leachate waters of closed landfills possible. Designers of waste management systems can analyse all the aspects of landfill closure using the modelling results and principles of greenbuilding presented in this study. Closure of landfills does not need to remain at the minimum level of environmental protection. By choosing an enduse suitable for the site and size of landfills, they can be taken into active use and as part of communal landuse.
  - The chosen types of surface structures for Finnish landfills which were tested in the study and which were taken into use on the grounds of this study, can be used in the surface structures of landfills. Their function, analysed by LCAM, in reducing and controlling infiltration, depends most on the hydraulic conductivity of the hydraulic barrier. Its material and hydraulic conductivity can be chosen according to the situation and the need. A risk assessment of the environmental consequences of the landfill must be first made in the choice of the type of surface structure and in the requirements.
  - In the design of surface structures it must be noted that, in practice, differential settlements, uneven compression of the underlying waste and frost will almost certainly produce cracks within the hydraulic barrier and increase the hydraulic conductivity. LCAM does not take into consideration cracks, which will probably develop in the hydraulic barrier with time and increase the hydraulic conductivity.
  - In the planning of the surface structure, a systematic and phased approach should be used, such as the one presented in this study.
- For the further development of landfill technology and minimizing the environmental consequences of landfills in Finland, the following measures, which have come to light for various reasons during this study, can be suggested.
- In the future it would be useful to continue the testing of LCAM under more controlled cir-

cumstances where the infiltration, the surface runoff and subsurface layer runoff can be measured separately, because in these test circumstances that was impossible.

- When infiltration caused by differential settlements, uneven compression of the underlying waste and frost are expected to cause a serious threat for ground- or surface waters, the use of bentonite mixes, geomembranes and geosynthetic clay liners in the hydraulic barrier must be taken into consideration because they are much better able to resist these kinds of damage than, for example, compacted clay. In using clay, it must be covered and prevented from drying. Also, the use of a temporary, relatively permeable cover and the collection of leachate water and treating the landfill as an active bioreactor before the construction of the final cover, and stabilizing the waste must be taken into consideration.
- Research on the frost protection of surface structures of landfills for the Finnish climate should be done. For example, the effect of the heat produced by the decomposition of the organic material on the frost depth and the thermal insulation of surface structures should be of special interest.
- The removal of snow from landfills is not a common practice at the moment in Finland. It should be taken into consideration as a cheap way to reduce infiltration into wastes whenever possible.
- A special code of practice for closing landfills situated on groundwater areas should be prepared.
- Inexpensive methods of stabilization, for example, when it is possible to improve the quality of poor soils for use in the hydraulic barrier, should be developed.
- How bentonite mixes endure in the surface structures of landfills in Finnish conditions should be researched.
- Research on the geotechnical properties of Finnish landfill wastes should be done.
- The suitability of geomembranes and geosynthetic clay liners in surface structures in the Finnish climate should be researched.
- The optimum conditions (temperature, moisture etc.) for the decomposition of wastes in the Finnish climate should be researched.
- The suitability of Finnish wastes should be researched, especially the pulp and paper indus-

try and other typical Finnish industrial wastes, for use in surface structures of landfills.

- A new type of the surface structure for landfills is known as a hydraulic barrier-structure (Hude and Jelinek 1933, Barres and Bonin 1993). The functioning of this structure should be tested in the laboratory and modelled in Finnish conditions.

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Helsinki, January 1997

Jouko Saarela

## Yhteenveto

Tässä työssä on tutkittu suljettujen kaatopaikkojen peitemateriaalien imeytymisominaisuuksien hydraulista arviointia.

Tutkimus aloitettiin keräämällä runsaasti esitietoja kaatopaikkojen käyttäytymisestä ja pintarakenteista Suomessa ja ulkomailla sekä tekemällä mm. valtakunnallinen inventointi aikaisemmin käytöstä poistetuista kaatopaikoista, jotta yleensä voitiin ryhtyä harkitsemaan ja suunnittelemaan tähän tutkimukseen liittyviä toimenpiteitä. Tutkimuksen vaiheet on esitetty kuvassa 1.

Tietoja verrattiin ulkomailla tehtyihin kaatopaikkoihin liittyviin tutkimuksiin, havaintoihin ja käytäntöön. Kerättyjen tietojen ja inventoinnin perusteella valittiin mm. Suomeen soveltuvat viiden eri tyyppisen kaatopaikan pintarakenteet, joita voidaan käyttää eri tyyppisissä ja kokoisissa kaatopaikoissa.

Laajojen kenttähavaintojen perusteella tutkimuksessa kehitettiin kokonaan uusi, erityisesti Suomen olosuhteisiin tarkoitettu kaatopaikkojen pintarakenteiden arviointimalli (LCAM). Mallilla voidaan arvioida kaatopaikkojen peittämiseen liittyvien eri tekijöiden, mm. eristyskerroksen vedenläpäisevyyden ja paksuuden, pintakerroksen vedenläpäisevyyden ja paksuuden, kasvillisuuden, lumenaurauksen ja kuivatuserroksen vaikutus kaatopaikan peiterakenteiden läpi imeytyvän sadannan määrään. Mallia kehitettäessä pyrittiin erityisesti siihen, että jätetäytön pF-käyrää ja vedenläpäisevyyttä ei tarvitse antaa mallille lähtötietoina, koska mm. aikaisempien tutkimuksien mukaan jätetäytön vedenläpäisevyys on niin suuri, että peite- ja eristyskerroksen vedenläpäisevyys on laskelmissa kriittinen tekijä. Mallilla saatuja tuloksia on silti syytä seurata ja testauksia jatkaa tulevaisuudessa eri olosuhteissa, koska tässä tutkimuksessa mallia voitiin testata vain rajoitetussa määrin.

Kaatopaikan peiterakenteiden läpi imeytyvään sadantaan vaikuttavien eri tekijöiden arvioinnissa voidaan käyttää tässä työssä esitettyjä suunnit-

teludiagrammeja (kuvat 50–54) ja tarkemmissa ja yksityiskohtaisemmissa tarkasteluissa kehitettyä kaatopaikkojen pintarakenteiden arviointimallia.

Suomen olosuhteisiin valittujen pintarakennetyyppien ominaisuudet analysoitiin kehitetyllä mallilla. Niiden toiminta suotovesien vähentämisessä riippuu eniten eristyskerroksen vedenläpäisevyydestä. Sen materiaali ja vedenläpäisevyys voidaan valita tilanteen ja tarpeen mukaan kaatopaikan ympäristövaikutusten arvioinnin yhteydessä, joka tulee tehdä jo ensimmäisessä vaiheessa kun kaatopaikkaa ryhdytään sulkemaan. Myös kasvillisuudella, lumenaurauksella ja kuivatuskerroksella voidaan vähentää sadannan imeytymistä jätteisiin.

Kaatopaikkojen sulkemisen käytännön toteuttamista varten tutkimuksessa on esitetty myös kaatopaikkojen sulkemisen vaiheittainen tarkastelutapa (kuva 58). Siinä tulee selvittää jo ensimmäisessä vaiheessa mm. se, ovatko pintarakenteet yleensä riittäviä estämään käytöstä poistettavien kaatopaikkojen ympäristöhaitat vai tarvitaanko lisäksi esim. pystyeristysrakenteita, suojapumpauksia pohjavesien virtaussuuntien muuttamiseksi, jätejakeiden erottelua tai jopa kaatopaikan siirtoa toiseen paikkaan. Vaiheittainen tarkastelutapa, johon sisältyy mm. mallintaminen ja viherkentämisen periaatteet, antaa jätehuollon suunnittelijoille, kunnille ja teollisuudelle mahdollisuuden hoitaa järkevästi ne jätehuollon tehtävät, jotka liittyvät kaatopaikkojen peittämiseen ja viimeistelyyn. Tällöin kaatopaikkojen loppukäsittelyn ei tarvitse rajoittua pelkästään ympäristönsuojelun kannalta välttämättömien toimenpiteiden tekemiseen. Kaatopaikat voidaan saada täten myös hyötykäyttöön osana kunnan maankäyttöä, kun niille valitaan sijaintiin ja kokoon sopiva jälki-

## List of Symbols

$\alpha_E$	ratio of actual and potential evapotranspiration	$E_{pot,c}$	potential evaporation from canopy (mm d <sup>-1</sup> )
$C_I$	parameter indicating the maximum value of interception storage (mm) (0.2..0.5)	$E_{pot,s}$	potential evaporation from bare soil (mm d <sup>-1</sup> )
$D_P$	the thickness of the surface layer (mm)	$E_{act,c}$	actual evaporation from canopy (mm d <sup>-1</sup> )
$E_{pot}$	potential evaporatranspiration calculated from meteorological variables (mm d <sup>-1</sup> )	$E_{act,s}$	actual evaporation from bare soil (mm d <sup>-1</sup> )
		ETS <sub>i</sub> , ETS <sub>i-1</sub>	effective temperature sum (dd) for days i and i-1
		$I_{LF}$	infiltration into landfill (mm d <sup>-1</sup> )
		$I_{slope}$	average slope of the landfill (m m <sup>-1</sup> )
		$K_b$	hydraulic conductivity of the hydraulic barrier layer (m s <sup>-1</sup> )
		$K_{ext}$	radiation extinction coefficient (0.5..0.7)
		$K_{CANOPY}$	quality of the canopy (0..10)
		$k_M$	degree-day factor for snowmelt (mm d <sup>-1</sup> °C <sup>-1</sup> )
		$K_{top}$	hydraulic conductivity of the surface layer (m s <sup>-1</sup> )
		LAI	leaf area index (m <sup>2</sup> m <sup>-2</sup> )
		LAI <sub>opt</sub>	leaf area index in optimal conditions (m <sup>2</sup> · m <sup>-2</sup> )
		$L_{slope}$	average length of the slope (m)
		$M$	snowmelt (mm d <sup>-1</sup> )
		$P_t$	precipitation (mm d <sup>-1</sup> )
		$R_{evapo}$	relative water content, below which too dry soils start to limit actual evaporation (0.6..0.8)
		$R_{E,c}$	evaporation factor for vegetation (usually 1.0)
		$R_{E,s}$	evaporation factor for bare soil (0.4..0.6)
		$R_{sub}$	subsurface runoff can be formed if relative water content in the vegetation layer is greater than this value (0.4..0.7)
		$R_W$	relative water content in the surface layer (W/W <sub>max</sub> )
		$R_{W,start}$	initial value for relative water content (0.5..0.7)
		$S_{I,max}$	maximum value for interception storage (mm)
		$S_{P,i-1}, S_{P,i}$	value of the depression storage for days i-1 and i
		$S_{P,max}$	maximum value for the depression storage (mm)
		$Q_{sub}$	subsurface runoff (mm d <sup>-1</sup> )
		$Q_{surf}$	surface runoff (mm d <sup>-1</sup> )
		$T_A$	daily average air temperature (°C)

$T_{base}$	base temperature for snowmelt ( $^{\circ}\text{C}$ )
$\Theta_p$	porosity ( $\text{m}^3 \text{ m}^{-3}$ )
$W$	water content in the surface layer (mm)
$W_{max}$	maximum value for water content in the surface layer (mm)
$W_{i-1}, W_i$	water content in the surface layer at the beginning and at the end of the day $i$ (mm)
$D_b$	thickness of the hydraulic barrier (mm)
$H_L$	hydraulic height in the bottom of the hydraulic barrier (mm)
$H_p$	the hydraulic height in the surface of the hydraulic barrier (mm)
$Q_D$	drainage layer runoff ( $\text{mm d}^{-1}$ )
$K_D$	hydraulic conductivity of the drainage layer ( $\text{m d}^{-1}$ )
$D_D$	thickness of the drainage layer (mm)
$H_{cr}$	critical height (m)
$\Delta N$	total settlement (m)
$\alpha$	coefficient which depends on field conditions
$N$	fill depth (m)
$t$	time (d)
$e$	initial void ratio
$\beta$	slope angle
$m$	settlement rate (feet per month)
$h$	soil water potential (m)
$K(h)$	hydraulic conductivity ( $\text{m d}^{-1}$ )
$z$	position of the vertical dimension (m) (positive downward from the surface)
$C(h)$	slope of the pF-curve ( $\text{m}^{-1}$ )
$S(h)$	loss term which takes evaporation and horizontal surface runoff ( $\text{cm}^3 \text{ cm}^{-3}$ ) into consideration
$K$	hydraulic conductivity of the landfill for horizontal flow ( $\text{m d}^{-1}$ )
$D$	saturated thickness of the landfill at time $t$ (m)
$H$	hydraulic head in the landfill at time $t$ (m)
$R$	net rate of recharge ( $\text{m d}^{-1}$ )
$S$	specific yield of the landfill ( $\text{m m}^{-1}$ )
$P$	net rate of abstraction (e.g. drainage) ( $\text{m d}^{-1}$ )
$\Theta$	soil moisture ( $\text{m}^3 \text{ m}^{-3}$ )
$\Theta_s$	saturated water content when all pores are filled with water ( $\text{m}^3 \text{ m}^{-3}$ )
$\mu$	soil parameter

$q$	flow velocity ( $\text{m d}^{-1}$ )
$K(\phi)$	hydraulic conductivity of the soil ( $\text{cm d}^{-1}$ ) (function of soil matric potential)
$K_s$	saturated hydraulic conductivity ( $\text{cm d}^{-1}$ )
$\phi$	matric potential (m)
$\phi_{max}$	matric potential limit (m)
$a_k$	soil parameter
$\alpha_k$	soil parameter
$[F]$	stiffness matrix
$\{H\}$	dependent variable vector (hydraulic head in the landfill)
$[D]$	capacity matrix
$\{Q\}$	flux vector representing sources and sinks
$\delta$	normal stress (MPa)
$\tau$	shear stress (MPa)

## Abbreviations

EPA	Environment Protection Agency
GCLs	geosynthetic clay liners
HDEP	high density polyethylene
HELP	Hydrologic Evaluation of Landfill Performance
HSSWDS	Hydrologic Simulation of Solid Waste Disposal Sites
LANCEL	Landfill Cellular Liquids Model
LCAM	Landfill Cover Approximation Model
NCASI	National Council of Paper Industry for Air and Stream Improvement Inc.
PL	investigation point
PV	groundwater tube
SCS	Soil Conservation Service
WBM	Water Balance Method

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## **Appendix 1**

### **Pilot investigations of surface parts of closed landfills for testing of LCAM**

<b>1 Pilot investigations of surface parts of closed landfills and factors to secure the suitability of landfills for testing .....</b>	<b>104</b>
1.1 Background .....	104
1.2 The investigation places and methods .....	104
1.2.1 Soil investigations .....	104
1.2.2 Greenbuilding and environmental investigations .....	109
<b>2 Results of the pilot investigation .....</b>	<b>109</b>
2.1 Weight sounding tests, water level measurements and soil investigations .....	109
2.2 Frost measurements .....	110
2.3 Moisture measurements .....	110
2.4 Nutrient analysis .....	111
2.5 Additional pilot investigations .....	115
2.5.1 Radon emanation .....	115
2.5.2 Analysis of chlorinated phenols .....	115
2.5.3 Analysis of polyaromatic compounds .....	115
2.5.4 Methane, hydrogen sulphide and oxygen measurements .....	116
2.6. Additional results of the pilot investigations .....	117
2.6.1. Detailed description of soil samples in the nutrient analysis .....	117
<b>3 Summary of pilot investigations and their use in the testing of LCAM and in its practical applications .....</b>	<b>120</b>
<b>References .....</b>	<b>120</b>

# 1 Pilot investigations of surface parts of closed landfills and factors to secure the suitability of landfills for testing of LCAM

## 1.1 Background

Landfill research is in many ways a new science and, as such, it has not yet standardized investigation, methods for different investigations. Therefore, one of the aims of these pilot investigations was to test the suitability of some standardized soil investigation methods for the proper testing of the of LCAM. Landfills can also contain many kinds of toxic materials. Therefore, some green-building and environmental investigations were also done to get a general conception of them in landfills. They must be considered in the practical applications of the modelling with LCAM, for example, in the greenbuilding which is an important factor in preventing infiltration of precipitation into wastefill.

## 1.2 The investigation places and methods

### 1.2.1 Soil investigations

The aim of the soil investigations was to investigate properties and behaviour of surface parts of the landfills at different seasons for proper testing investigations of LCAM. Investigations were made at the Iso-Huopalahti, Mankkaa and Vuosaari landfills near Helsinki (Table 1, Figs 1, 2, 3, 4). Weight sounding tests, disturbed soil samples, measurement of groundwater levels and measurements of frost depth and moisture were used as investigation methods.

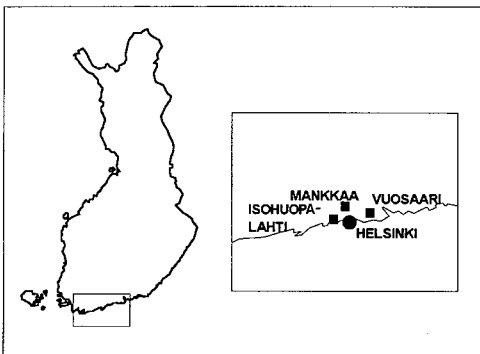


Fig. 1. Landfills where pilot investigations were conducted.

Weight sounding tests, the taking of disturbed soil samples and installation of groundwater tubes were done with a multiple-use drill (A-sondi 304). Weight sounding tests were done according to Finnish standards described in Suomen Geoteknillinen Yhdistys ry. (1980). Disturbed soil samples were taken according to the Finnish standards described in Suomen Geoteknillinen Yhdistys ry. (1976). Measurement of the groundwater levels was done according to the Finnish standards described in Suomen Geoteknillinen Yhdistys ry. (1975).

Measurement of frost depths was done according to the Finnish standards described by National Board of Waters (1984).

Moisture measurements were done with the Nea-moisture measurement device. The measurement method is described by Tattari and Granlund (1989).

The aim of the weight sounding tests was to investigate the sounding resistance of surface parts of the landfills. The investigation lines of weight sounding tests were chosen so that they represented the whole landfill in the best possible way. Two groundwater tubes, and two frost measurement tubes were installed in each landfill. However, on the Iso-Huopalahti landfill it was impossible to install groundwater tubes due to the lightness of the multiple-use drill and the great difficulty in penetrating waste materials, for example, large amounts of concrete.

Samples were taken with a multiple-use drill (auger-spits, diameter 65 mm, sampling length 200 mm inner diameter 25 mm). Groundwater tubes were iron tubes (inner diameter 26 mm, length of sieve 1–2 m, diameters of holes 3 mm). Frost measurement tubes were installed in the plastic protection tubes (diameter 19.3 mm) and they were plastic pipes filled with methyl blue liquid. Iron tubes (diameter 40 mm) served as neutron tube.

Nine weight sounding tests were done on the Iso-Huopalahti landfill at the depth of 0.0–2.5 m on the investigation line, which was 425 m long. Totally 26 samples were taken from the depth of 0.5–2.5 m. Frost measurement tubes were installed at the depth of 4 m. Neutron measurement tubes were installed at the depth of 2 metres on the top and on the slope (Fig. 2).

Totally 13 weight soundings were done on the Mankkaa landfill at the depth of 0.0–3.4 m on the investigation line, which was 550 m long. Totally 38 samples were taken from the depth of 0.0–2.7 m.

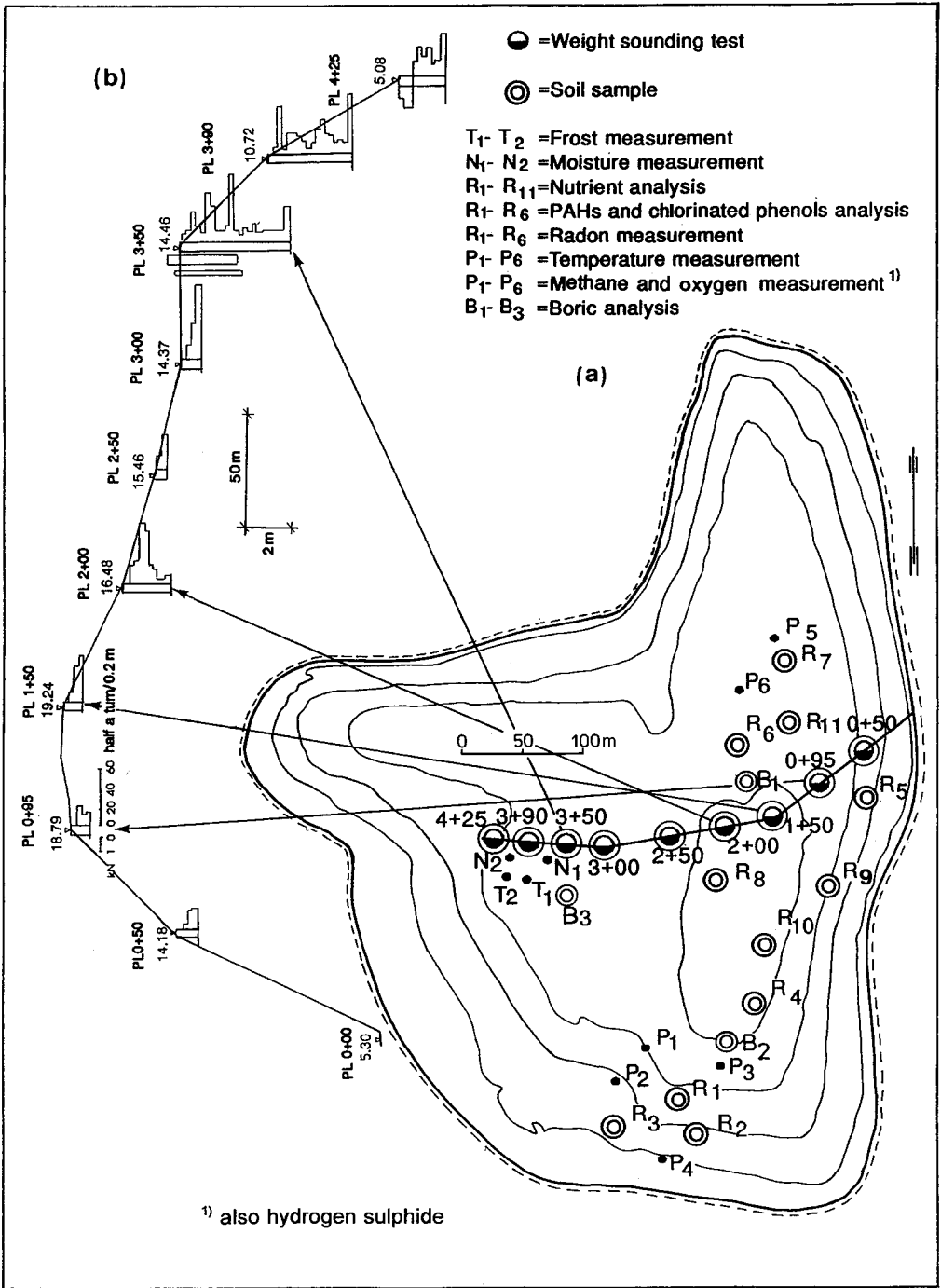
Groundwater tubes were installed at the depth of 6 m. Neutron tubes were installed at the depth of 2 m on the top and on the slope (Fig. 3).

Eight weight sounding tests were done on the Vuosaari landfill at the depth of 0.0–3.5 m on the investigation line, which was 260 m long. Eight samples were taken from the depth of 0.0–2.2 m. Groundwater tubes were installed at the depth of 6 m. Frost measurement tubes were installed at the depth of 2 m on the top and on the slope. Neutron measurement tubes were installed at the depth of 2 m on the top and on the slope (Fig. 4).

Water content, hydraulic conductivity, and dry unit weight of the surface samples (depth 0.0–0.25 m) were investigated from the samples taken in the weight soundings by the waste and soil laboratory of the Technical Research Office of the Water and Environment Research Institute. Hydraulic conductivity (constant head test) of the disturbed soil samples and other geotechnical laboratory tests of the soil samples were measured and done according to Finnish standards described by Tie- ja vesirakennushallitus (1970b).

**Table 1.** Soil investigations conducted on the Iso-Huopalahti, Mankkaa and Vuosaari landfills.

Landfill	Investi- gation point	Investigation type								
		Weight sound- ing	Sampling		Ground- water measure- ment		Frost measurement		Moisture measurement	
		depth m	depth m	number	depth m	number	depth m	number	depth m	number
Iso-Huo- palahti	PI 0+50	0.0-1.2	0.0-1.2	3	-	-	-	-	-	-
	PI 0+95	0.0-1.0	0.0-1.0	3	-	-	-	-	-	-
	PI 1+50	0.0-1.2	0.0-1.2	3	-	-	-	-	-	-
	PI 2+00	0.0-1.2	0.0-1.2	4	-	-	-	-	-	-
	PI 2+50	0.0-0.5	0.0-0.5	2	-	-	-	-	-	-
	PI 3+00	0.0-1.2	0.0-1.2	2	-	-	-	-	-	-
	PI 3+50	0.0-1.0	0.0-1.0	4			4	1	2	1
	PI 3+90	0.0-2.5	0.0-2.5	3			4	1	2	1
	PI 4+25	0.0-1.5	0.0-1.5	2	-	-	-	-	-	-
Mankkaa	PI 0+00	0.0-2.3	—		-	-	-	-	-	-
	PI 0+25	0.0-2.4	0.0-2.7	9	6	1	4	1	2	1
	PI 1+00	0.0-3.4	0.0-1.2	4	6	1	4	1	2	1
	PI 1+50	0.0-1.0	0.0-1.6	6	-	-	-	-	-	-
	PI 2+00	0.0-1.2	0.0-1.2	4	-	-	-	-	-	-
	PI 2+50	0.0-1.6	0.0-1.2	2	-	-	-	-	-	-
	PI 3+00	0.0-1.4	0.0-1.0	2	-	-	-	-	-	-
	PI 3+50	0.0-1.0	0.0-1.0	3	-	-	-	-	-	-
	PI 4+00	0.0-1.0	0.0-0.6	2	-	-	-	-	-	-
	PI 4+25	—	0.0-0.5	1	-	-	-	-	-	-
Vuosaari	PI 4+50	0.0-1.0	0.0-0.9	3	-	-	-	-	-	-
	PI 5+00	0.0-1.0	0.0-0.5	1	-	-	-	-	-	-
	PI 5+50	0.0-1.0	0.0-0.3	1	-	-	-	-	-	-
	PI 0+50	0.0-3.3	0.1-0.6	2	6	1	4	1	2	1
	PI 0+85	0.0-3.5	0.0-0.5	2	6	1	4	1	2	1
	PI 1+10	0.0-0.9	0.0-1.0	3	-	-	-	-	-	-
	PI 1+60	0.0-0.9	0.1-1.1	4	-	-	-	-	-	-
	PI 1+85	0.0-0.8	—	-	-	-	-	-	-	-
	PI 2+10	0.0-3.6	0.0-1.0	3	-	-	-	-	-	-
	PI 2+35	0.0-4.0	—	-	-	-	-	-	-	-
	PI 2+60	0.0-2.4	0.0-2.2	4	-	-	-	-	-	-



**Fig. 2.** Field investigations at the Iso-Huopalahti landfill. Investigation lines (a) and height profile and weight sounding tests on the investigation line (b). Difficult to penetrate wastes, for example, pieces of concrete and other hard material made weight sounding tests difficult in almost all investigation points.

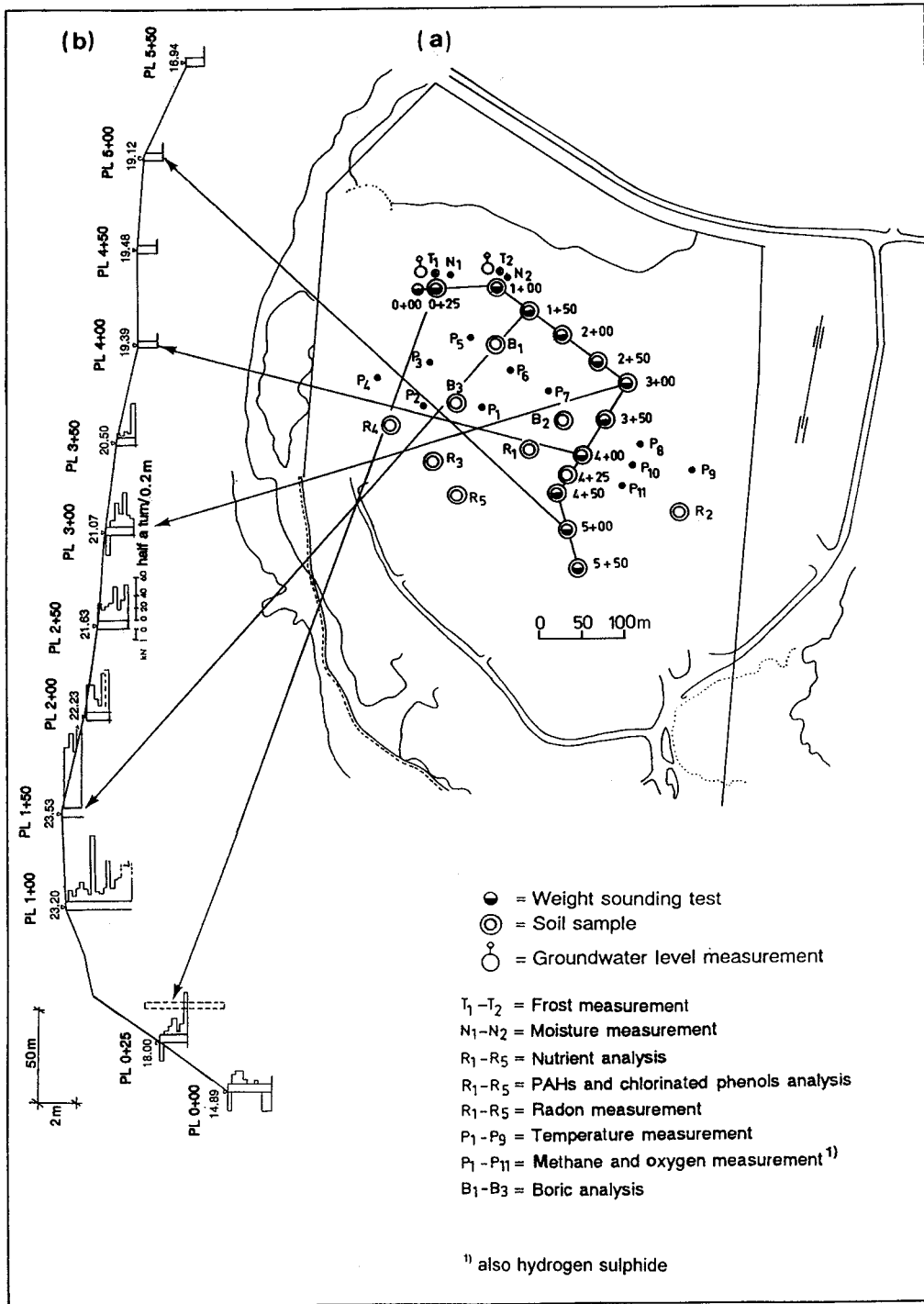
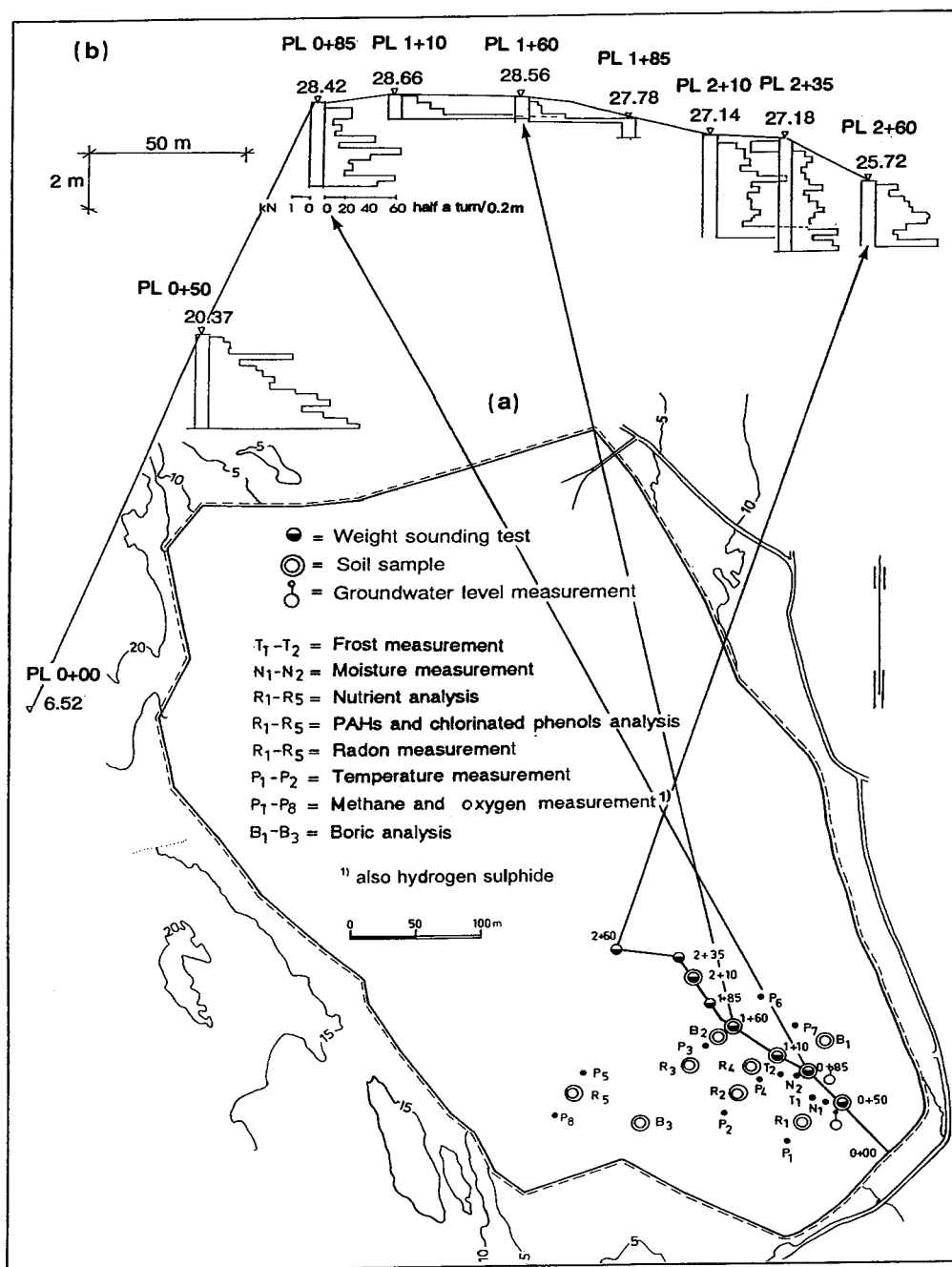


Fig. 3. Field investigations done at the Mankkaa landfill. Investigation lines (a) and height profile and weight sounding tests on the investigation line (b). Pieces of concrete made weight sounding tests difficult in almost all investigation points.



**Fig. 4.** Field investigations at the Vuosaari landfill. Investigation lines (a) and height profile and weight sounding tests on the investigation line (b). Pieces of concrete made weight sounding tests difficult in almost all investigation points.

## 1.2.2 Greenbuilding and environmental investigations

In greenbuilding investigations, the nutrient content of surface soils was investigated by taking samples from the surface parts of the landfills and analysing their nutrient content. The meaning of the environmental investigations was to clarify whether there was anything alarming in the landscaping and enduse of landfills.

The investigations were done at the Iso-Huopalahti, Mankkaa and Vuosaari landfills.

Specific electrical conductivity, pH, nitrate nitrogen, phosphorus, potassium, calcium, magnesium and boric content of samples were analysed in the nutrient analysis. There were 11 samples from Iso-Huopalahti and 5 from the Mankkaa and 5 from Vuosaari landfills. For boric analysis, 3 samples were taken from each landfill.

The nutrients were analysed according to the Finnish standards for nutrient analysis of soil samples for greenbuilding described by Kähäri *et al.* (1987).

Radon was analysed, because it is a common problem in southern Finland and therefore pilot investigations concerning radon were also done. High radon contents are toxic for man. High radon contents of landfills prevent enduse for any recreational purpose. Measurements were made from composite samples according to methods described by Markkanen and Arvela (1992).

Chlorinated phenols and polyaromatic compounds are environmental poisons, which can in many ways hinder the enduse of landfills. They can be a problem if, for example, a landfill is taken into active enduse and surface soils contain these environmental poisons. Then the contaminated soils must first be removed. They were measured from composite samples according to the method described by Keith (1981).

On all landfills, oxygen, methane and hydrogen sulphide measurements were made with a portable Crowcon triple 84TR measurement device. Temperature measurements in the surface parts of landfills were also done with a thermometer probe.

## 2 Results of the pilot investigation

### 2.1 Weight sounding tests, water level measurements and soil investigations

According to the results, resistance of weight sounding tests varied considerably on all landfills. At different points they could be classified from loose to tight (Tie- ja vesirakennushallitus 1970a). Difficulty to penetrate wastes, for example, pieces of concrete, made weight sounding tests difficult at almost all investigation points. Therefore light multiple-use drills were not suitable for landfill investigations. Characteristics of surface soils determined from the samples were the following: hydraulic conductivity of surface samples (0-25 cm) at Iso-Huopalahti, Mankkaa and Vuosaari landfills varied  $10^{-6.0}$ – $10^{-9.1}$  m s<sup>-1</sup>, water content 15.3–86.9 %, and dry unit weight 8.6–16.5 kN m<sup>-3</sup> (Table 2).

Weight sounding tests, frost, water content and groundwater measurements on the slopes of the investigation landfills are shown in Figs 5, 6 and 7.

On the Mankkaa and Vuosaari landfills the water levels were measured in 1991 from two investigation points once a month on both landfills. On the Mankkaa landfill on April 3rd 1991 the water level was highest and it was 110 cm from the surface of the slope (Fig. 6). In other measurements it was 117–247 cm from the surface of the slope. Only one measurement was obtained on Vuosaari on 3.4.1991 and the water level was 245 cm from the surface of the slope.

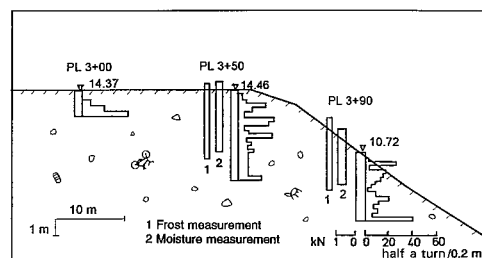
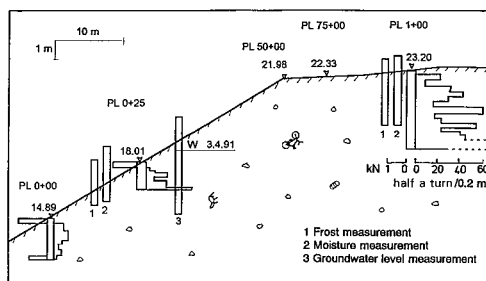
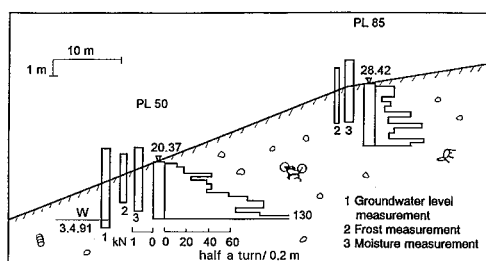


Fig. 5. Weight sounding tests, frost and moisture measurements on the slope of the Iso-Huopalahti landfill. It was impossible to install groundwater tubes due to the lightness of the multiple-use drill and the difficult to penetrate waste materials, for example, large pieces of concrete and other hard material.



**Fig 6.** Weight sounding tests, frost, moisture and groundwater measurements on the slope of the Mankkaa landfill. Groundwater level could be measured only from the lower investigation point.



**Fig. 7.** Weight sounding tests, frost, moisture and groundwater measurements on the slope of the Vuosaari landfill. The groundwater level could be measured only from the lower investigation point.

**Table 2.** The results of the laboratory investigations of the soil samples in the pilot investigations.

Landfill	Depth of sample m	Hydraulic conductivity $m s^{-1}$	Water content %	Dry unit weight $kN m^{-3}$
Iso-Huopalahti	0-0.25	$10^{-6.0}$	15.3–	8.6–
		$10^{-8.5}$	55.3	16.5
Mankkaa	0-0.27	$10^{-6.6}$	9.0–	9.7–
		$10^{-9.1}$	86.9	16.4
Vuosaari	0-0.22	$10^{-7.2}$	13.9–	11.5–
		$10^{-8.8}$	25.8	15.5

## 2.2 Frost measurements

The frost depths were measured in the winters of 1991–1992 on the tops and on the slopes of the Iso-Huopalahti, Mankkaa and Vuosaari landfills. It was found that the greatest frost depth was on the slope of the Vuosaari landfill and it was 90

cm. On the Mankkaa landfill the greatest frost depth was 64 cm (top) and in Iso-Huopalahti it was 52 cm (top). Most of the measurement points had no snow as the wind had blown it away (Fig. 8).

Soveri and Varjo (1977) investigated and reported maximum frost depths in the period 1955–1975 on snow-free till areas. In the coastal area of southern Finland the frost depth was 120 cm and the freezing index was between 10 000–15 000 h °C.

During this investigation, the freezing index in the winters of 1991–1992 was about 9 000 h °C. From the results it could be deduced that the results of this investigation are much the same as the results of Ettala (1986). According to his investigations, the frost depth at landfills was, on average, less than in natural areas. This is due evidently to the decomposition of organic material, which produces heat.

It must be noted that the frost depth can vary in different landfills due to the age of the landfill, type of waste etc., which have effects on the temperature of the waste. The effect of the temperature of wastes on the frost depth must, if needed, be measured or calculated, because the new landfill technology aims e.g. to enlarge, centralize and increase the height of landfills. It can be supposed that the temperatures of landfills are in future higher which will decrease the frost depth.

## 2.3 Moisture measurements

Moisture content investigations as a function of the impulses of the neutron tube were made on the Iso-Huopalahti, Mankkaa and Vuosaari landfills between 4.1.1991–20.11.1991. Two tubes, one on the top and other on the slope, were installed for neutrontube measurements on each landfills.

Moisture content profiles were measured to the depth of two metres. The measurements were made every 10 cm to the depth of one metre and thereafter every 20 cm. The surface measurement at a depth of 10 cm was unsure because in summer, part of the neutrons are expelled to the atmosphere and in the winter the snow causes errors. Results were presented as the number of impulses, the higher the number of impulses the more moisture the surface layer contained. Water content was not given as a moisture percentage or in millimetres because wastes could contain materials which could absorb neutrons and cause errors in the cali-



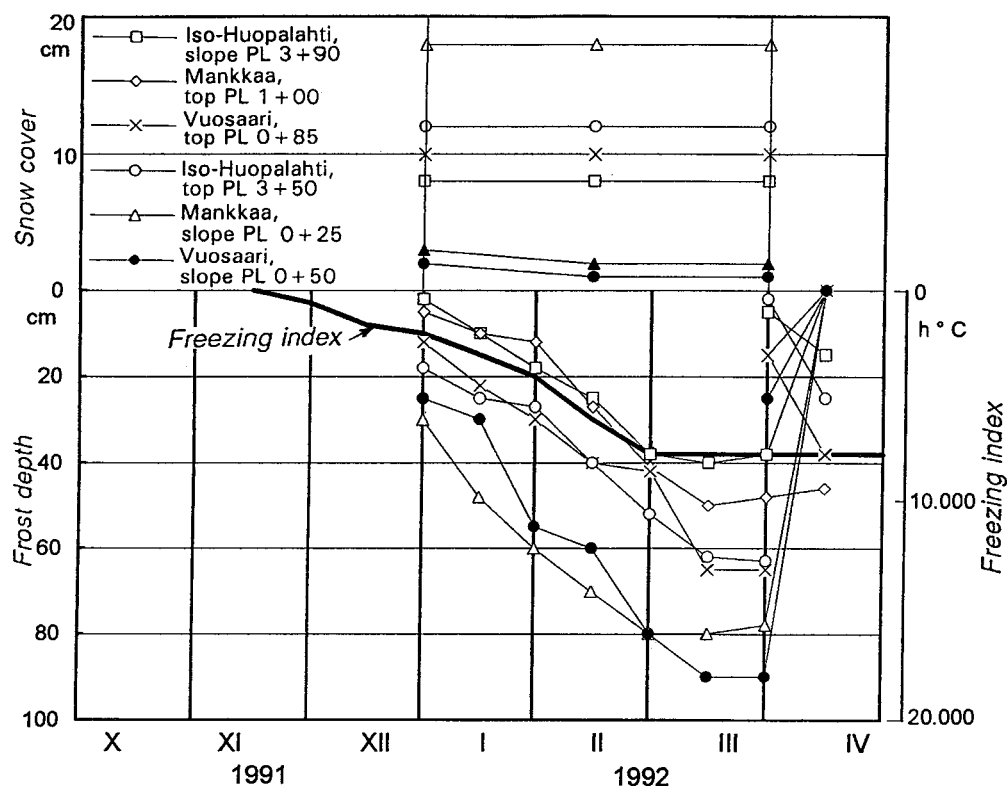


Fig. 8. The frost depth in the Iso-Huopalahti, Mankkaa and Vuosaari landfills in the winters of 1991–1992. It was found that the greatest frost depth was on the slope of the Vuosaari landfill and it was 90 cm.

bration. Impulses however, described relative variations of moisture in relation to time, because it is supposed that during the research period the substance is the same. The time of the measurement at each depth was 30 s.

At the top of landfills, the greatest changes in moisture were in the surface layer of depth 50 cm. In the measurement profiles, the stratified structure of the surface layer and wastes was seen clearly. Layer structures were different on each landfill which demonstrates their individual structure. The greatest changes in moisture content were observed in the surface layer in March and April, and the smallest in July–August. These changes were caused by the infiltration of melting snow in the spring, and the increase of evapotranspiration in the summer. Measurement changes deeper in the landfills were, in general, small (Fig. 9).

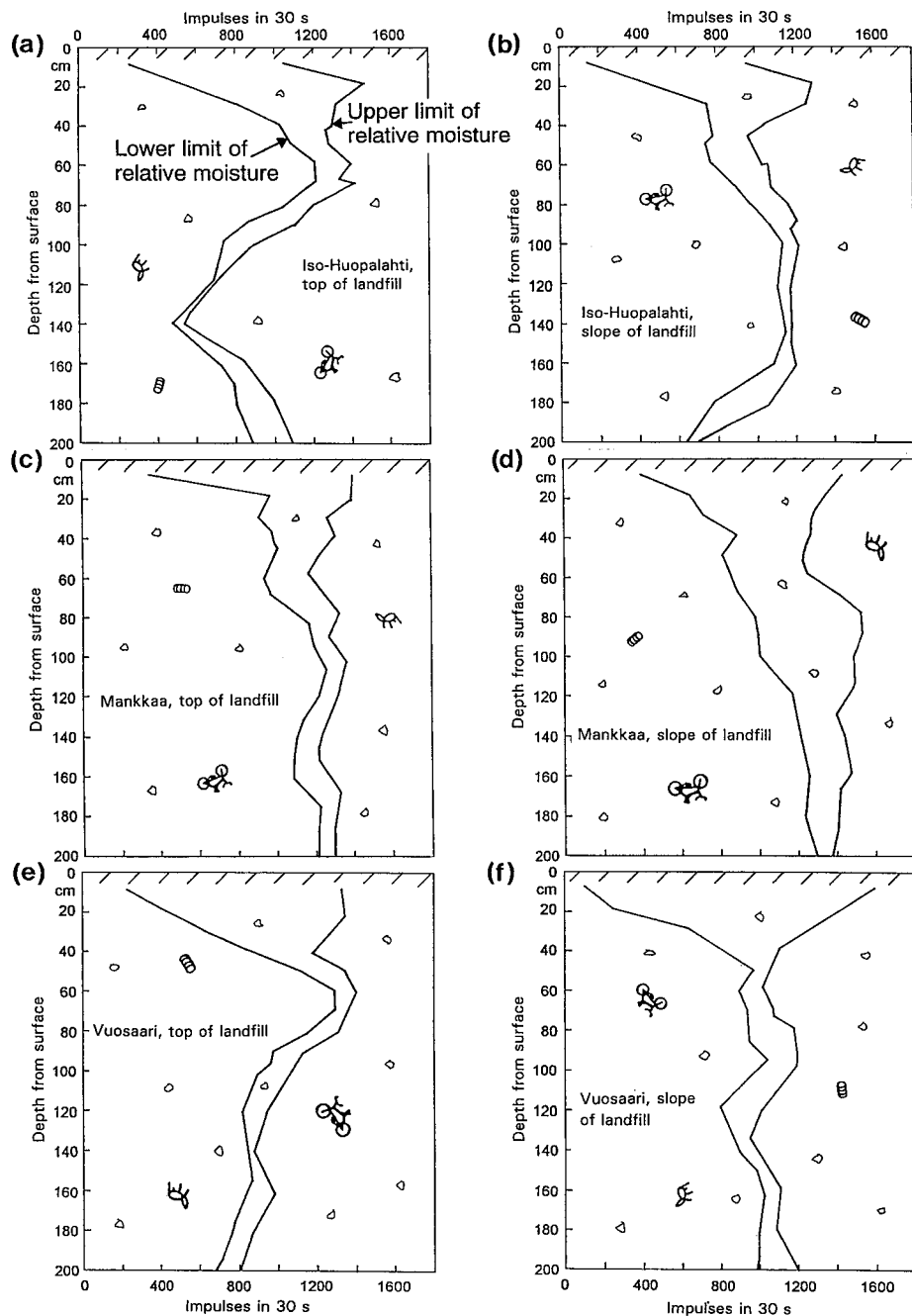
On the slopes, the greatest changes were also in

the surface layer 50 cm deep. Stratified layer structures were also seen clearly in these profiles. Also at these points were the greatest and smallest moisture contents, in the spring and at the end of summer respectively. The high water level on the slope of the Mankkaa landfill was clearly seen in the measurement results (Figs 6, 9 d).

## 2.4 Nutrient analysis

The nutrient content of surface soils was investigated in the laboratory from soil samples from the Iso-Huopalahti, Mankkaa and Vuosaari landfills. Specific electrical conductivity, acidity, nitrate nitrogen, phosphorus, potassium, calcium and magnesium and boric were analysed.

Results of the analyses are shown in Tables 3, 5, 6. Results of the analyses were compared to the Finnish recommendations on greenbuilding. It was



**Fig. 9.** Moisture measurements as a function of the impulses of the neutron tube measurements at the Iso-Huopalahti landfill (a,b) at the Mankkaa landfill (c,d) and at the Vuosaari landfill (e,f). The greatest changes in the moisture were on the 50 cm deep surface layer. In the measurement profiles the stratified structure of the surface layer and wastes was seen clearly. The measurement device was not calibrated to wastes and it gave only relative values of moisture. For comparison with estimates for sandy soil, 1 400 impulses in 30 seconds is a water content of about 36 % and 1 000 impulses in 30 seconds is a water content of about 22 %.

**Table 3.** Results of nutrient analysis of the Iso-Huopalahti landfill (Viljavuuspalvelu Oy).

Investigation point	Specific electrical conductivity $\mu\text{S cm}^{-1}$	pH	Nutrient content $\text{mg l}^{-1}$				
			( $\text{NO}_3\text{-N}$ )	P	K	Ca	Mg
1	220	5.1	7.2	46.0	130	1 850	225
2	110	6.3	19.0	28.0	240	2 650	200
3	50	5.7	2.8	2.5	105	600	100
4	60	6.1	5.8	1.9	95	72	60
5	310	5.7	18.0	70.0	580	2 600	350
6	130	5.8	34.0	20.0	390	1 175	90
7	30	5.6	5.0	1.0	25	200	10
8	870	6.3	38.0	24.0	170	3 950	445
9	140	6.7	30.0	29.0	190	3 750	300
10	560	6.4	24.0	28.0	265	3 700	520
11	190	7.1	2.8	540.0	140	4 000	425

**Table 4.** Recommended nutrient additions for grass and bush planting for the Iso-Huopalahti landfill (Viljavuuspalvelu Oy).

Investigation point	Recommended nutrient additions					
	Limed and fertilized peat $\text{m}^3 100 \text{ m}^{-2}$	Mineral soil $\text{m}^3 100 \text{ m}^{-2}$	Dolomite $\text{kg } 100 \text{ m}^{-2}$	Garden lime $\text{kg } 100 \text{ m}^{-2}$	Garden Y-fertilizer $\text{kg } 100 \text{ m}^{-2}$	Potassium sulphate $\text{kg } 100 \text{ m}^{-2}$
1		6	70	5		2
2	3			5		
3	5		30	5	5	
4	5		20	5	5	
5			30			
6	3		30	3	1	
7	5		30	5	6	
8						
9	3			4	3	
10				5		
11				2		

**Table 5.** Results of nutrient analysis of the Mankkaa landfill (Viljavuuspalvelu Oy).

Investigation point	Specific electrical conductivity $\mu\text{S cm}^{-1}$	pH	Nutrient content $\text{mg l}^{-1}$				
			( $\text{NO}_3\text{-N}$ )	P	K	Ca	Mg
1	80	6.3	2.1	6.8	120	1 300	300
2	120	6.4	4.2	75.0	140	1 700	140
3	180	6.0	1.5	22.0	95	1 600	145
4	260	5.9	1.4	140	85	1 400	255
5	70	5.6	1.3	5.8	120	1 100	200

**Table 6.** Results of nutrient analysis of the Vuosaari landfill (Viljavuuspalvelu Oy).

Investigation point	Specific electrical conductivity $\mu\text{S cm}^{-1}$	pH	Nutrient content $\text{mg l}^{-1}$				
			( $\text{NO}_3\text{-N}$ )	P	K	Ca	Mg
1	140	6.3	4.2	2.2	200	1 700	280
2	160	6.8	3.5	11.0	175	2 300	225
3	100	7.3	4.4	1.5	220	700	590
4	70	6.5	2.0	2.1	240	1 900	325
5	120	7.3	6.0	9.0	180	3 000	195

**Table 7.** Result of boric analysis of surface samples (Viljavuuspalvelu Oy).

Landfill	Sample	pH	Boric $\mu\text{g l}^{-1}$	Content of boric
Mankkaa	1	5.0	100	poor
"	2	5.9	400	rather poor
"	3	6.3	2 100	precariously high
Iso-Huopalahti	4	6.8	1 900	high
"	5	6.1	300	poor
"	6	5.6	700	rather good
Vuosaari	7	5.9	1 000	good
"	8	7.7	1 400	good
"	9	5.9	300	poor

clearly seen that almost all samples needed several different nutrient additions to support vegetation. Recommendations for nutrient additions for the landfill of Iso-Huopalahti are shown in Table 4. It can be seen, for example, that samples from the Iso-Huopalahti landfill need limed and fertilized peat, mineral soil and dolomite. Detailed descriptions of the samples are presented in Chapter 2.6.

Results of boric analysis are shown in Table 7. They varied between 100 to 1 900  $\mu\text{g l}^{-1}$  and the variation of contents was from low to precariously high.

In summary, it is very important to do nutrient analysis in the vegetation and landscaping of landfills because soils used on the landfills are, in general, poor in nutrients and need nutrient additions.

## 2.5 Additional pilot investigations

### 2.5.1 Radon emanation

Radon emanation was measured from composite samples from all three landfills. Results of the

measurements are shown in Table 8. By comparing the results of the measurements to typical radon emanation in loose soils in southern Finland (Table 9), it was seen that radon emanation was on the same level and there was nothing alarming concerning radon on the landfills in question.

### 2.5.2 Analysis of chlorinated phenols

Chlorinated phenols were analysed from the composite samples. Results of the analysis are shown in Table 10. By comparing the results to the values used in the estimation of soil contamination (Ympäristöministeriö 1994), it was seen that the values were low and chlorinated phenols were not a risk for the enduse of the landfills in question (Table 11).

### 2.5.3 Analysis of polyaromatic compounds

Polyaromatic compounds were analysed from the composite samples. Results of the analysis are

**Table 8.** Results of measurements of radon emanation. Natural radionuclides (Säteilyturvakeskus).

Landfill	$^{226}\text{Ra}$ $\text{Bq kg}^{-1}$	$^{232}\text{Th}$ $\text{Bq kg}^{-1}$	$^{40}\text{K}$ $\text{Bq kg}^{-1}$	Em %	Radon emanation $\text{mBq h}^{-1} \text{kg}^{-1}$
Iso-Huopalahti	38 (6)	35 (7)	490 (5)	8 (26)*	23 (27)7*
Mankkaa	30 (6)	37 (6)	670 (5)	26 (6)**	59 (9)**
Vuosaari	47 (6)	46 (6)	820 (5)	15 (13)	53 (14)**

( ) percentage errors

\* room dry sample

\*\* moisture content 5 % (weight)

**Table 9.** Typical values of radon emanations in loose soils in southern Finland (Säteilyturvakeskus).

Natural radionuclides	Typical value in loose soils in southern Finland	
$^{226}\text{Ra}$	30–80	$\text{Bq kg}^{-1}$
$^{232}\text{Th}$	30–80	$\text{Bq kg}^{-1}$
$^{40}\text{K}$	700–1 500	$\text{Bq kg}^{-1}$
radon emanation dry, sample	20–100	$\text{mBq h}^{-1} \text{kg}^{-1}$
moisture content 5 % (weight)	40–200	$\text{mBq h}^{-1} \text{kg}^{-1}$

**Table 10.** Results of the analysis of chlorinated phenols (Ympäristöntutkimuskeskus).

Landfill	2, 4, 6-trichlorophenol	2, 4, 5 trichlorophenol	penta-chlorophenol	dry content of sample
	$\mu\text{g kg}^{-1}$	$\mu\text{g kg}^{-1}$	$\mu\text{g kg}^{-1}$	%
Iso-Huopalahti	0.1	1.0	2.6	60.69
Mankkaa	0.6	—	—	43.57
Vuosaari	—	—	0.9	82.66
analysed chlorinated phenols				
1. 2,6-dichlorophenol			8. 4,5,6-trichloroquaiacol	
2. 2,4/2,5-dichlorophenol			9. Pentachlorophenol	
			10. 3,4,5-trichlorocatanol	
3. 2,4,6-trichlorophenol			11. Tetrachloroquaiacol	
4. 2,4,5-trichlorophenol			12. 3,4,5-trichloro-2,6-dimethoxyphenol	
5. 4,5-dichloroquaiacol			13. Tetrachlorocatechol	
6. 2,3,4,6-tetrachlorophenol				
7. 3,4,5-trichloroquaiacol				

Values are for dry samples

**Table 11.** Limit values of chlorinated phenols (Ympäristöministeriö 1994).

Chlorinated phenols	Typical value in soil	Value for soil to be classified as contaminated
	$\mu\text{g kg}^{-1}$	$\mu\text{g kg}^{-1}$
2, 4, 6-trichlorophenol	2 000	10 000
2, 4, 5 trichlorophenol	2 000	25 000
penta-chlorophenol	400	4 000

shown in Table 12. By comparing the results to the values used in the estimation of the contamination of soil (Ympäristöministeriö 1994), it was seen that the values were low and polyaromatic compounds were not a risk for the enduse of the landfills in question (Table 13).

#### 2.5.4 Methane, hydrogen sulphide and oxygen measurements

Methane, hydrogen sulphide and oxygen were measured from several points of the landfills (Ta-

bles 14, 15, 16). There were no gas removing systems in the investigation landfills. The smell of methane was observed in some parts of all landfills and it caused nausea in researchers. Methane is explosive at an atmospheric concentration of 5-15 %. The methane, oxygen, and hydrogen sulphide contents of the surface layers of the landfills were measured at several points. The methane content, at many points, was in the limits of explosive danger (5-15%) and oxygen content between 10-20 % of the volume. According to *Duel et al.* (1986) methane discharging sites cannot be landscaped without methane removing systems. Also *Neumann* (1979) has stated that vegetation will not succeed properly if the level of oxygen in the soil is lower than 12-14%. Hydrogen sulphide was detected in only one point on the Iso-Huopalahti landfill. In this research, scientific vegetation observations were not made. However, it was clearly seen that there was no vegetation in several places where methane erupted to the surface.

Temperature measurements were also made from several points on the landfills. The purpose of temperature measurement was to measure temperatures where methane erupted to the surface. In particular, high temperatures (max +46°C) were measured at such points on the Iso-Huopalahti landfill.

According to *Neumann* (1979), if the temperature on the landfill is over +25°C it is not wise to

Table 12. Results of analysis of polyaromatic compounds (Ympäristöntutkimuskeskus).

Land-fill	Fluoranthene	Pyrene	Chrysene	Benzo(b)-fluoranthene	Benzo(k)-fluoranthene	Benzo(a)pyrene	Benzo(ghi)-perylene	Dry content of sample	Total PAH
	$\mu\text{g kg}^{-1}$	$\mu\text{g kg}^{-1}$	$\mu\text{g kg}^{-1}$	$\mu\text{g kg}^{-1}$	$\mu\text{g kg}^{-1}$	$\mu\text{g kg}^{-1}$	$\mu\text{g kg}^{-1}$	%	$\mu\text{g kg}^{-1}$
Mankkaa	31	-	141	92	11	68	17	43.57	360
Vuosaari	53	45	90	20	7	40	14	82.66	269
Iso-Huopalahti	200	43	232	71	20	130	31	60.69	727

PAH-compounds:	Limit of measurement
Fluoranthene	0.5 $\mu\text{g kg}^{-1}$
Pyrene	5 $\mu\text{g kg}^{-1}$
Chrysene	2 $\mu\text{g kg}^{-1}$
Benzo(k)fluoranthene	0.1 $\mu\text{g kg}^{-1}$
Bonzo(a)pyrene	0.1 $\mu\text{g kg}^{-1}$
Benzo(ghi)perylene	5 $\mu\text{g kg}^{-1}$

Values are for dry samples

Table 13. Limiting values of polyaromatic compounds (Ympäristöministeriö 1994).

Polyaromatic compound	Typical value in soil	Limiting value in soil to be classified as contaminated
	$\mu\text{g kg}^{-1}$	$\mu\text{g kg}^{-1}$
Fluoranthene	1,000	40,000
Pyrene	4,000	40,000
Chrysene	2,000	40,000
Benzo(k)-fluoranthene	2,000	40,000
Benzo(a)-pyrene	2,000	40,000
Benzo(ghi)-perylene	2,000	40,000
Total PAH	20 000	200 000
	0	0

landscape it. Also, high methane contents disturb the vegetation. High temperatures in the landfill cause, according to Vainio (1984), extra evapotranspiration, and the concentration of salts and nutrients in the surface which causes drying of vegetation.

## 2.6 Additional results of the pilot investigations

### 2.6.1 Detailed description of soil samples in the nutrient analysis

#### Iso-Huopalahti landfill:

Sample 1 was a mixture of mineral soil and barking waste. It is too light as such, so a silt moraine type of soil should be added to it. The pH-value was low, the calcium and potassium levels were quite low, the phosphorus and magnesium levels were good.

Sample 2 was a rather coarse-grained soil which requires extra peat to improve the water and nutrient retaining capacity.

The pH-value and the studied nutrient level were fairly good.

Sample 3 was a good type of soil but due to its poor humus content it requires extra peat. The pH-value was low, the phosphorus level was very low and the other studied nutrients were low.

Sample 4 was a good type of soil, but due to its poor humus content, it requires extra peat. The pH-value was fairly good, the studied nutrients were very low.

**Table 14.** Results of methane, oxygen, and hydrogen sulphide measurements at the Iso-Huopalahti landfill, in summer 1990.

Investi- gation point	Oxygen  %	Methane  %	Hydrogen sulphide  ppm	Depth of mea- surement cm	Obs.
1	1	5–15	-	10–40	no vegetation
2		<5	-	10–40	good vegetation
3	11	5–15	33	10–40	poor vegetation
4	12	5–15	-	10–40	poor vegetation
5	19	<5	-	10–40	good vegetation
6	16	<5	-	10–40	good pine plantings

**Table 15.** Results of methane, oxygen, and hydrogen sulphide measurements at the Mankkaa landfill in summer 1990.

Investi- gation point	Oxygen  %	Methane  %	Hydrogen sulphide  ppm	Depth of mea- surement cm	Obs.
1	23	<5	-	20	planted deciduous trees
2	20	5–15	-	20	no vegetation
3	3	5–15	-	20	no vegetation
4	20	5–15	-	20	no vegetation
5	21	5–15	-	20	airfield for models, thin grass
6	20	<5	-	20	planted deciduous trees
7	19	5–15	-	20	-"-
8	21	<5	-	30	pinus
9	19	5–15	-	40	-"-
10	15	5–15	-	30	mainly weed
11	19	5–15	-	30	mainly weeds and small pine plants

Sample 5 was a good type of soil with a good humus content. The pH-value was rather low, the potassium level was high and the other studied nutrients were good.

Sample 6 was a good type of soil, but the humus content was not quite sufficient.

Sample 7 was a rather fine-grained soil, and especially for lawns, extra peat is necessary, coarser

mineral soil could also be added to the lawn. The soil was acid and the entire nutrient sample was poor.

In sample 8 the specific electrical conductivity was high in comparison to the studied nutrients. This type of soil is recommended to be used only in soil mixtures where the other soil's specific electrical conductivity is low. On the basis of this study



**Table 16.** Results of methane, oxygen and hydrogen sulphide measurements at the Vuosaari landfill in summer 1990.

Investi- gation point	Oxygen  %	Methane  %	Hydrogen sulphide  ppm	Depth of mea- surement cm	Obs.
1	14	5–15	-	25	smell of methane, no vegetation, gravel
2	19	<5	-	20	good vegetation
3	16	5–15	-	30	no vegetation, gravel
4	17	<5	-	25	good vegetation
5	8	5–15	-	30	no vegetation, gravel
6	19	<5	-	25	humus, soil
7	17	5–15	-	35	..-
8	17	5–15	-	20	no vegetation

its proportion could be at the most 1/3. Liming and fertilization depends on the nutrient content of other soil mixtures.

Sample 9 was a rather coarse-grained type of soil and requires extra peat to improve the water and nutrient retaining capacity.

The pH-value, calcium and magnesium levels were good, the potassium and phosphorus levels were fairly good.

Sample 10 was a good type of soil with a good humus content. The specific electrical conductivity was rather high than comparison with the studied nutrient content, the phosphorus level was rather low, the other studied nutrients were good.

Sample 11 was a good type of soil with a good humus content. The pH-value, the calcium and the phosphorus levels were high, the magnesium level was good and the potassium level was rather low.

#### *Mankkaa landfill*

Sample 1 was sandy clay with humus. As a greenbuilding material this type of soil requires extra soil improvement agents, peat and sand. The pH-value was good, so was the magnesium level, the calcium and potassium levels were low and the phosphorus level was low.

Sample 2 could be classified as mud. It could also be of very decomposed barking waste. This

type of soil was not suitable solely as a substrate in ecological greenbuilding, rather it requires a sand moraine type of mineral soil. The pH-value, calcium, phosphorus and magnesium levels were fairly low and the potassium level was low.

Sample 3 was humus soil and too light for greenbuilding. It should be increased in mineral soil content. Calcium, pH, phosphorus and magnesium are good and potassium was low.

Sample 4 was a humus type of soil and as such, slightly too light. It requires extra sand moraine type of mineral soil. The pH-value, calcium and phosphorus levels were fairly low, the magnesium level was good and the potassium level was low.

Sample 5 was a sandy clay type of soil and has a humus content. In greenbuilding, this type of soil requires extra soil improvement agents, peat and sand. The pH-value, calcium and phosphorus levels were low, the potassium level was fairly low and the magnesium level was good.

#### *Vuosaari landfill*

Sample 1 was a sandy clay type of soil. In particular, as the substrate for grass, the clay becomes airtight. In order to improve the composition of the soil it was necessary to add at least the recommended quantities of extra peat and sand. The

pH-value and calcium level were rather low, the potassium and magnesium levels were good and the phosphorus level was extremely low.

Sample 2 was a sandy clay type of soil. In particular, as the substrate for grass, the clay becomes airtight. In order to improve the composition of the soil it was necessary to add at least the recommended quantities of extra peat and sand. The pH-value, the calcium and magnesium levels were good, the potassium and the phosphorus levels were fairly low.

Sample 3 was a silty clay type of soil. In order to improve the composition it was necessary to add at least the recommended quantities of extra peat and sand. The pH-value was too high, the calcium, potassium and magnesium levels were good and the phosphorus level was extremely low.

Sample 4 was a sandy clay type of soil. In particular, as the substrate for grass the clay becomes airtight. In order to improve the composition it is necessary to add at least the recommended quantities of extra peat and sand. The pH-value, the calcium, potassium and magnesium levels were good and the phosphorus level was extremely low.

Sample 5 was a sandy clay type of soil. In particular, as the substrate for grass, the clay becomes airtight. In order to improve the composition it was necessary to add at least the recommended quantities of extra peat and sand. The pH-value was high, the calcium level was good, the magnesium level was adequate and the potassium and phosphorus levels were fairly low.

### 3 Summary of pilot investigations and their use in the testing of LCAM and in its practical applications

The following describes the use of pilot investigations in the proper testing of LCAM and in practical applications of modelling.

- Measured hydraulic conductivities gave background information of the values of hydraulic conductivity of surface structures for modelling. They were used as preliminary limit values of the hydraulic conductivity of the surface structures in the development of the LCAM.
- Light multiple-use drills were not suitable for landfill investigations. This was due to the fact that landfills, in general, contain waste materials that are difficult to penetrate, for example,

pieces of concrete, which make weight sounding tests difficult. Therefore, in the testings of LCAM, heavy multiple-use drills were used.

- From the water levels it was seen that the water table can change greatly in different parts of the landfills and it can be far from the surface of the landfills. This was considered in planning the measurements of water levels in the testings of LCAM.
- Frost depths gave background information for the modelling about the thickness of surface soil layers on top of the hydraulic barrier.
- From the moisture measurements it was seen that the greatest changes of moisture on the landfills were in the 50 cm thick surface layer. It was used as background information in choosing the layer thicknesses in the simulation calculations by LCAM.
- From nutrient analysis it was seen that surface soils on landfills can be poor in nutrients and they need nutrient additions. It was taken into consideration in the practical applications of modelling because good vegetation has great importance in reducing the infiltration.
- Radon emanation was on the same level as typical radon emanation in loose soils in southern Finland. Values of chlorinated phenols and polycyclic aromatic compounds were also low. They were taken into consideration in practical applications of modelling.
- The smell of landfill gas was observed in some parts of all investigation landfills. It, for example, caused nausea in researchers. Landfill gas can also be harmful for vegetation and after use, if methane removing structures are not installed.

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## **Appendix 2**

### **Summary of the national survey of closed landfills**

#### **Contents**

<b>1 Introduction .....</b>	<b>123</b>
<b>2 Survey results .....</b>	<b>123</b>
2.1 General .....	123
2.2 Number of landfills .....	123
2.3 Foundation and closing years of landfills .....	125
2.4 Quality of wastes .....	125
2.5 Height and area .....	129
2.6 Material of cover structures .....	130
2.7 Failures .....	130
2.8 Erosion of slopes .....	130
2.9 Enduse .....	130
2.10 Landscaping .....	131
2.11 Removal of landfills .....	131
2.12 Control of leachate waters .....	131
2.13 Environmental consequences of landfills .....	132
<b>3 Conclusions .....</b>	<b>132</b>
<b>References .....</b>	<b>133</b>

# 1 Introduction

According to the national landfill register there were 644 open landfills in Finland in 1994 of which 446 were used primarily for municipal solid waste disposal (Table 1). According to the register 162 landfills had been closed. Due to inadequate registration, the total number of the closed landfills is probably higher than reported.

**Table 1.** Number of landfills in Finland in 1994.

Type of landfill	Open	Closed	Planned	Status not known	Total
Municipal solid waste	446	940	3	2	1 391
Hazardous waste	11	18	-	-	29
Industrial waste	14	5	-	-	19
Inert waste	79	48	-	-	127
Landfill for special waste fraction	89	113	-	1	203
Not known	5	38	-	5	48
Total	644	1 162	3	8	1 817

The number of open landfills in Finland is high compared, for example, to Sweden where in 1993 there were about 300 landfills (Table 2). The Finnish Ministry of the Environment has set a target to cut the number of landfills to 200–250 by the year 2000. The aim is to encourage communities to cooperate in waste management and to set up common landfills. Therefore, for example, the size of landfills will grow in future.

It is seen that almost 500 landfills will be closed in Finland by the end of this century. Therefore, the National Board of Waters and the Environment (from March 1st, 1995 the Finnish Environment Institute) initiated a research project concerning closure of landfills in 1990. In this survey, which was a part of the project, a national survey of landfills, which had been closed during the last 20 years, was carried out.

The survey examined larger landfills storing household and industrial wastes chosen randomly.

The aim of the survey was to investigate how closed landfills were covered and to make recommendations for measures to improve the practice of landfill coverage for Finnish conditions. The survey was done in 1990.

The following matters were clarified in the survey: name of landfill, foundation and closing year, locality, quality of waste, height, area, slope, failures, material of cover structures control of leachate waters, environmental consequences of leachate waters, landscaping and afteruse.

**Table 2.** Number of open municipal solid waste landfills in some Baltic Sea countries (Kettunen 1995).

Country	No. of landfills	Reference
Sweden	c. 300	Naturvårdsverket (1993)
Germany	c. 300	Mennerich (1994)
Lithuania	326	Kunevicius (1994)
Poland	c. 700	Kowalik (1994)

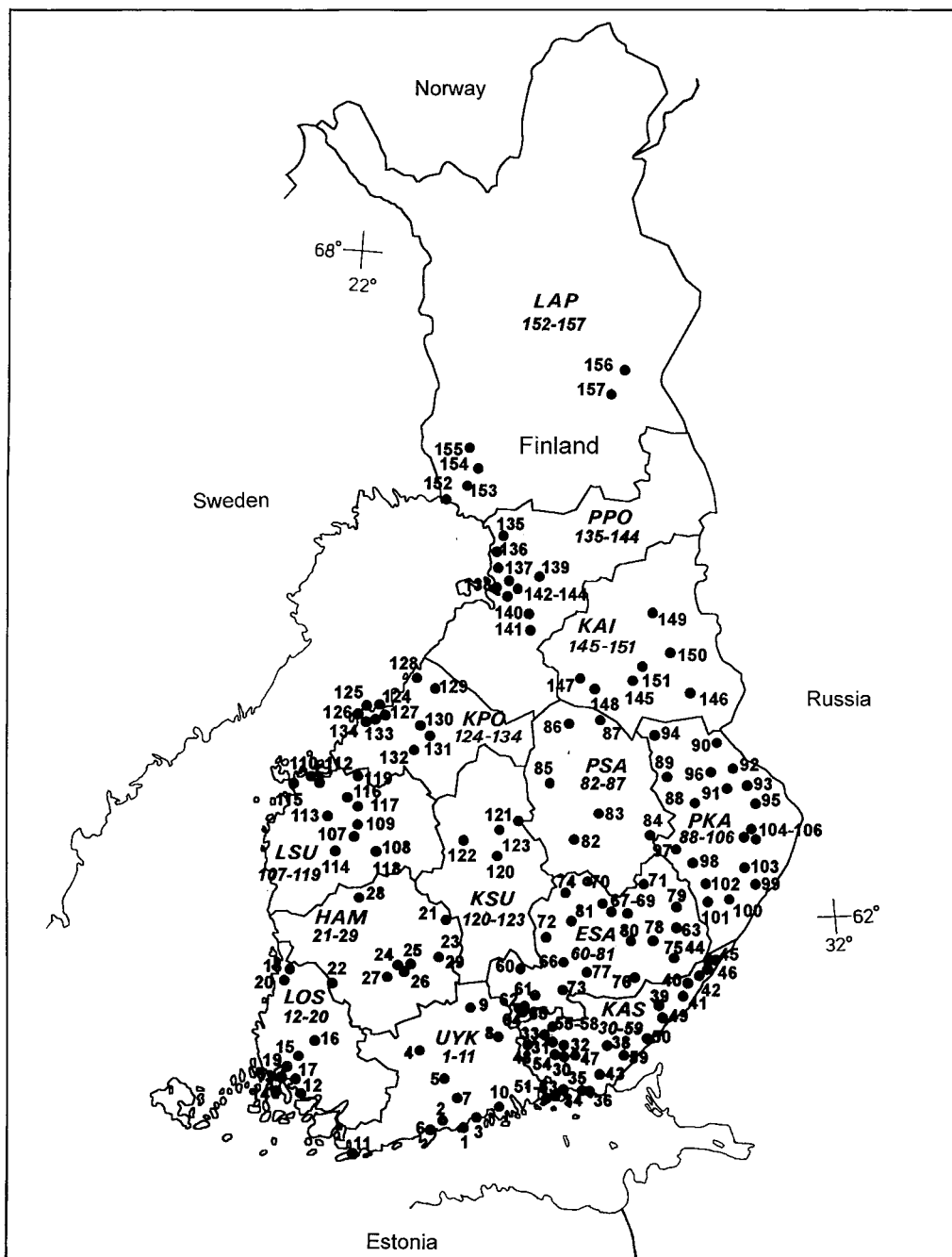
# 2 Survey results

## 2.1 General

Table 4 shows the number of landfills and names of the landfills in the survey classified according to the regional environment centres. Figs 2–12 show the results of the survey as percentage distributions. The results were based on field investigations and interviews concerning closure, coverage, technical data for the coverage of landfills, leachate waters and their environmental consequences. They are based on the research materials of the Finnish Environment Institute, consultants, municipalities, cities and water protection associations. Fig. 1 shows the landfills surveyed in this study classified according to the regional environment centres.

## 2.2 Number of landfills

The number of landfills varied in the regional environment centres from 4 to 30 landfills. The variations were, for example, due to population size, industry and general practice concerning waste management (Table 3).



**Fig. 1.** The landfills surveyed in this study classified according to the regional environment centres. The numbers refer to Tables 3 and 4.

**Table 3.** Number of landfills classified according to the regional environment centres.

Regional environment centre		Number of landfills	Numbers of landfills in Tab. 4 and in Fig.1
Uusimaa	(UYK)	11	1– 11
Southwest Finland	(LOS)	9	12– 20
Häme	(HAM)	9	21– 29
Southeast Finland	(KAS)	30	30– 59
South Savo	(ESA)	22	60– 81
North Savo	(PSA)	6	82– 87
North Karelia	(PKA)	19	88–106
West Finland	(LSU)	13	107–119
Central Finland	(KSU)	4	120–123
Central Ostrobothnia	(KPO)	11	124–134
North Ostrobothnia	(PPO)	10	135–144
Kainuu	(KAI)	7	145–151
Lapland	(LAP)	6	152–157

### 2.3 Foundation and closing years of landfills

The foundation year was known for less than 40 % of landfills and the closing year was known for almost all landfills. Almost 30 % of the landfills were founded in the 1960s and 55 % of the landfills were closed in the 1980s. The age of the majority of landfills was 15–20 years (about 40 %) (Figs 2, 3, 4).

### 2.4 Quality of wastes

In the survey 48 % of landfills were for household and industrial wastes, 46 % of landfills were only for household wastes, and 6 % of the landfills were only for industrial wastes. Landfills which were only for household wastes were, in general, in small localities where there was no industry. The industrial landfills were, in general, in industrial areas (Fig. 5).

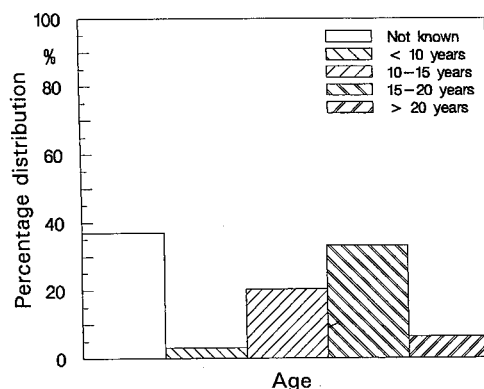
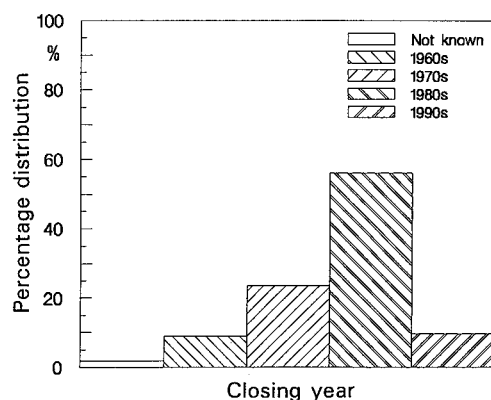
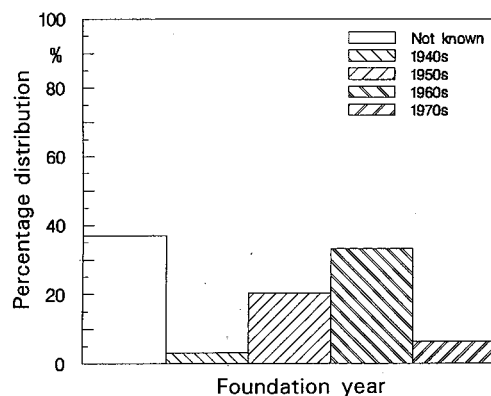
**Fig. 2.** The foundation years of landfills as a percentage distribution.**Fig. 3.** The closing years of landfills as a percentage distribution.**Fig. 4.** The age of landfills as a percentage distribution.

Table 4. Closed landfills in the survey.

No.	REC	Name of landfill and location (old landfill = vk)	No.	REC	Name of landfill and location
1	UYK	Iso-Huopalahti Helsinki	24	HAM	Lakalaiva Tampere
2	"	Mankkaa Espoo	25	"	Hervanta Tampere
3	"	Vuosaari Helsinki	26	"	Ikuri Tampere
4	"	Renko Janakkala	27	"	Pirkkala, vk Pirkkala
5	"	Terrisuo Tuusula	28	"	Kihniö, vk Kihniö
6	"	Volsi Kirkkonummi	29	"	Luopioinen, vk Luopioinen
7	"	Sotunki Vantaa	30	KAS	Hutsuo Anjalankoski
8	"	Hollola, vk Hollola	31	"	Mataroja I/ Myllykoski Oy
9	"	Lammi, vk Lammi	32	"	Anjalankoski Mataroja II/ Myllykoski Oy
10	"	Porvoo, vk Porvoo			Anjalankoski
11	"	Hanko, vk Hanko	33	"	Saksanaho, vk Kuusankoski
12	LOS	Peltola Turku	34	"	A. Ahlström Oy, vk Kotka
13	"	Iilinjärvi Naantali	35	"	Hovinsaari Kotka
14	"	Rymättylä Rymättylä	36	"	Muuralankuja Kotka
15	"	Mäksmäki Masku	37	"	Koskela Luumäki
16	"	Nousiainen, vk Nousiainen	38	"	Nuppola Luumäki
17	"	Raumantie Raisio	39	"	Kokkomäki Ruokolahti
18	"	Luotsinmäki Pori	40	"	Roihankylmii Parikkala
19	"	Kähärintie Rusko	41	"	Särkisalmi Parikkala
20	"	Vähä-Amerikka Pori	42	"	Ristiharju Parikkala
21	HAM	Vuohijoki Mänttä	43	"	Meltti Hamina
22	"	Äetsä, vk Äetsä	44	"	Saari, vk Saari
23	"	Yliskylä Orivesi	45	"	Kesusmaa Saari



Table 4 continued

No.	REC	Name of landfill and location (old landfill = vk)	No.	REC	Name of landfill and location
46	KAS	Korvenkylä	69	ESA	Kaitainen
47	"	Anjalankoski			Joroinen
48	"	Karhunkangas	70	"	Kirkonkylä, vk
		Anjalankoski			Jäppilä
49	"	Iitti, vk	71	"	Kirkonkylä, vk
		Iitti			Kangaslampi
50	"	Ruokolampi	72	"	Kirkonkylä, vk
		Imatra			Kangasniemi
51	"	Ukonlinna	73	"	Kirkonkylä, vk
		Imatra			Mäntyharju
52	"	Siltalankylä	74	"	Paltanen
		Pyhtää			Pieksämäki
53	"	Kirkonkylä, vk	75	"	Punkasalmi
		Pyhtää			Punkaharju
54	"	Oy Stockfors Ab	76	"	Kirkonkylä, vk
		Pyhtää			Puumala
55	"	Melkumäki	77	"	Arpiola
		Kuusankoski			Ristiina
56	"	Summa	78	"	Viohonsuo
		Vehkalahti			Savonlinna
57	"	Neuvoton	79	"	Kirkonkylä, vk
		Vehkalahti			Savonranta
58	"	Husula	80	"	Kirkonkylä, vk
		Vehkalahti			Sulkava
59	"	Vehkjärvi	81	"	Kirkonkylä, vk
		Vehkalahti			Virtasalmi
60	ESA	Lahnajärvi	82	PSA	Luokkisuo
		Ylämaa			Kuopio
61	"	Lesti	83	"	Teerimäki
		Hartola			Juvankoski
62	"	Rautvuori	84	"	Tulisalmi
		Heinola			Tuusniemi
63	"	Pormestarin suo	85	"	Kirkonkylä, vk
		Heinola			Pielavesi
64	"	Uusisuo	86	"	Kirkonkylä, vk
		Enonkoski			Vieremä
65	"	Laakkola	87	"	Kirkonkylä, vk
		Haukivuori			Sonkajärvi
66	"	Kippasuo	88	PKA	Turunkangas
		Heinola			Juuka
67	"	Pöyrynkylä, vk	89	"	Nurmes, vk
		Hirvensalmi			Nurmes
68	"	Kirkonkylä, vk	90	"	Vieikki
		Joroinen			Liekksa
69	"	Kuvansi	91	"	Mätäsvaara
		Joroinen			Liekksa

**Table 4** continued

No.	REC	Name of landfill and location (old landfill = vk)	No.	REC	Name of landfill and location
92	PKA	Vuonisahti	114	LSU	Huissi
		Liekka			Ilmajoki
93	"	Hattuvaara	115	"	Raippaluoto
		Liekka			Mustasaari
94	"	Valtimo, vk	116	"	Ekokytö
		Valtimo			Ylihärmä
95	"	Pankakoski, vk (Enso-Gutzeit Oy)	117	"	Kainasto
		Liekka			Ylistaro
96	"	Liekka, vk	118	"	Luoma
		Liekka			Peräseinäjoki
97	"	Viinijärvi	119	"	Hakola
		Liperi			Alahärmä
98	"	Niva	120	KSU	Sirkkasuo
		Liperi			Suolahti
99	"	Onkamo	121	"	Kalaniemi
		Tohmajärvi			Konginkangas
100	"	Kankaanrinta	122	"	Hukanmäki
		Rääkkylä			Saarijärvi
101	"	Hypenniemi	123	"	Köntysmäki
		Rääkkylä			Tikkakoski
102	"	Haapasalmi	124	KPO	Kirkonmäki
		Rääkkylä			Kokkola
103	"	Uimaharju, vk	125	"	Kokkola, vk 1
		Eno			Kokkola
104	"	Naurisoja	126	"	Kokkola, vk 2
		Eno			Kokkola
105	"	Harpatti	127	"	Rimmi
		Eno			Kokkola
106	"	Penttilä	128	"	Kalajoki, vk
		Joensuu			Kalajoki
107	LSU	Lellunneva	129	"	Alavieska, vk
		Seinäjoki			Alavieska
108	"	Rumavuori	130	"	Ullava, vk 1
		Kuortane			Ullava
109	"	Kiikku	131	"	Ullava, vk 2
		Nurmo			Ullava
110	"	Tuovila	132	"	Kirkkoharju
		Mustasaari			Kaustinen
111	"	Sulva	133	"	Linnusperä
		Mustasaari			Kokkola
112	"	Björköby	134	"	Soko-oja
		Mustasaari			Kokkola
113	"	Orismala	135	PPO	Olhava
		Isokyrö			Ii

Table 4 continued.

No.	REC	Name of landfill and location (old landfill = vk)	No.	REC	Name of landfill and location
136	PPO	Soronen	147	KAI	Kuusiranta
137	"	Ii			Vuolijoki
138	"	Rytisuo	148	"	Otamäki
		Haukipudas			Vuolijoki
139	"	Saviharju	149	"	Ruijanmeri
		Oulu			Hyrnsalmi
140	"	Yli-Kiiminki, vk	150	"	Ristijärvi
		Yli-Kiiminki			Ristijärvi
141	"	Sanginjoki, vk	151	"	Kontiomäki, vk
		Muhos			Paltamo
142	"	Laitasaari, vk	152	LAP	Liakka
		Muhos			Tornio
143	"	Iinatti	153	"	Anterovaara
		Oulu			Keminmaa
144	"	Toppilan tehdas	154	"	Kaitaharju
		Oulu			Tervola
145	"	Veitsiluoto Oy, vk	155	"	Peurapalo
		Oulu			Tervola
146	KAI	Maasto	156	"	Salla, vk
		Kajaani			Salla
147	"	Multikangas	157	"	Kursu
		Kuhmo			Salla

REC = Regional Environment Centre

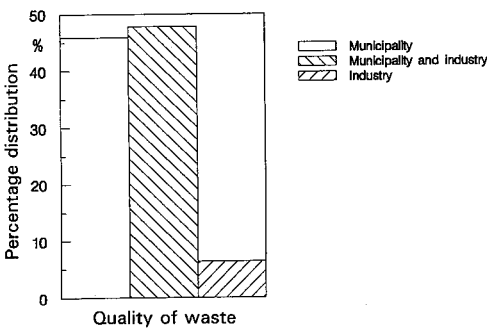


Fig. 5. The quality of wastes in landfills as a percentage distribution.

## 2.5 Height and area

The height of the majority of landfills was under 5 m (55 %). About 25 % of landfills were between 5–10 m and 15 % were between 10–15 m. About 10 % of landfills were over 20 m high (Fig. 6).

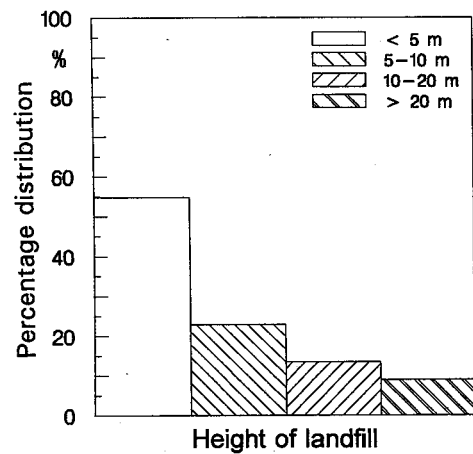


Fig. 6. The height of landfills as a percentage distribution.

The area of the majority of landfills was less than 0.5 hectare (about 40 %). About 30 % of landfills were 0.5–2 hectares and about 15 % were be-

tween 2–5 hectares. About more than 6 % of landfills were 5–10 hectares and about 10 % of landfills were over 10 hectares (Fig. 7).

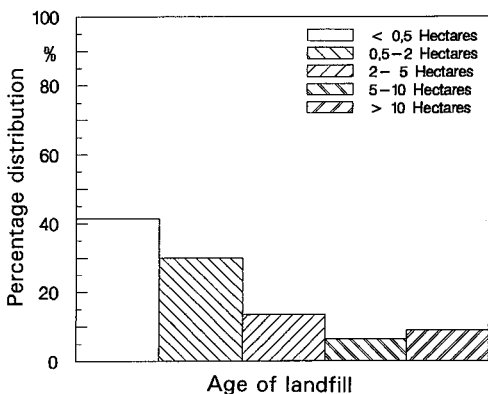


Fig. 7. The area of landfills as a percentage distribution.

## 2.6 Material of cover structures

The majority of landfills were covered by excess soil (65 %). In those cases the landscaping of landfills was also, in general, very poor. Sand and silt were used as materials for cover structures in 6 % of landfills, gravel and moraine together covered 6 % of landfills, clay 6 %, humus soil 1 % and moraine 8 % of landfills. Other materials such as peat, wood chips and asphalt were covers for 7 % of landfills. The thickness of the cover structures varied greatly. The greatest thickness of surplus soils was over 20 m and the smallest under 0.5 m. In a few cases there was a vegetation layer on the landfills and its thickness varied between 0.1–0.3 m. In most cases the surface structures were poor at minimizing leachate waters and in landscaping. Only a few landfills had a good vegetation layer. Only two landfills had gas removing structures (Fig. 8).

## 2.7 Failures

There have been failures in landfills in Finland. In the autumn of 1985 there was a failure in the Mankkaa landfill. It was caused by the placing of loose soil on the landfill (Tonteri and Lindroos 1987; Viatak Oy 1990). In the Iso-Huopalahti and Vuosaari landfills there have been failures due to the wrongfull placing of loose soil in 1980. Before dam safety legislation in Finland, there had been several failures of sludge ponds in landfills

(Saarela 1986, 1988). The reasons for failures have been inadequate planning, construction and overfilling of sludge pond dams.

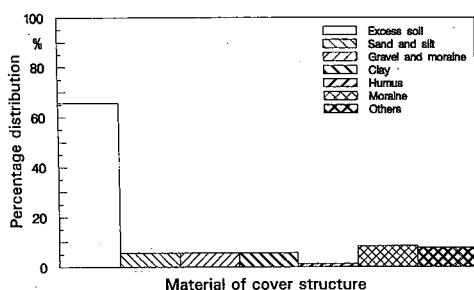


Fig. 8. The material of cover structures as a percentage distribution.

## 2.8 Erosion of slopes

The greatest erosion failures found were in the Renko and Tuusniemi landfills (nos 4 and 84 in Table 4). On the nonvegetated parts of the slope on one 100 m wide strip there were erosion failures which were between 1–2 m and their depth was 20–30 cm. The slope was 1:2 and the length was 10 m. There was also a slope of the same type in an area with vegetation and it had no erosion failures. On the Tuusniemi landfill a dense soil layer was built in the summer 1990. The vegetation surface was going to be built the next summer. However, in only a few months there were deep and great erosion failures on the slopes of the landfill. The depth of the erosion failures was 20–30 cm and they were between 1–2 m on the slope. The length of the slope was 20 m and the breadth was 100 m and slope 1:2.

On the basis of this it can be said that on gentle slopes great erosion failures can develop in a short time if there is no vegetation to prevent erosion. On the other hand, the slope can be deep and erosion failures do not develop if there is vegetation which prevents erosion.

## 2.9 Enduse

The majority of landfills did not have a proper enduse (80 %). The most developed enduse were green and recreation areas built on landfills, where many kinds of activities took place. There was, for example, an airfield for airplane models on the Mankkaa landfill, on the Iso-Huopalahti

there was a training area for equestrian sports and on several landfills there were motor sports areas. Other ways of enduse were storage areas for industry, compost areas and storage areas for surplus soils. Training areas for dogs and a feeding area for wild animals were planned for some landfills. From the results it was seen that the majority of landfills have not been included in the active landuse of the community (Fig. 9).

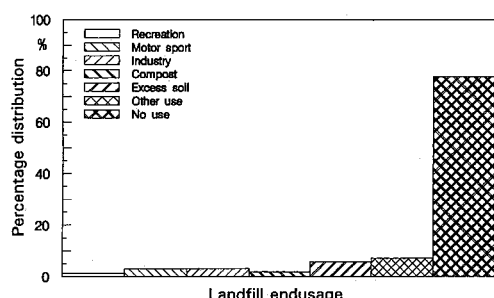


Fig. 9. Landfill endusage as a percentage distribution.

## 2.10 Landscaping

The majority of landfills were not landscaped (70 %). Complete landscaping was done on 9 % of landfills and partly on 12 % of landfills. Landscaped landfills were situated, in general, near large cities (Fig. 10).

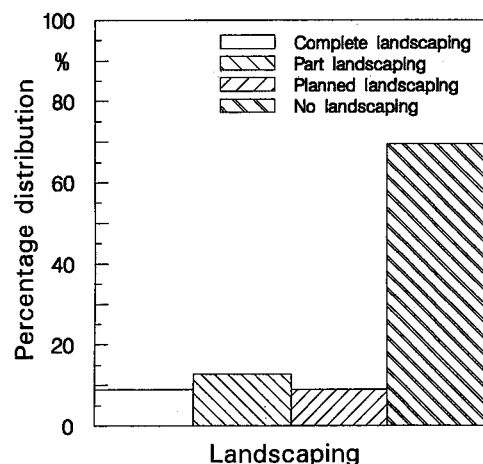


Fig. 10. Landscaping of landfills as a percentage distribution.

Landscaping should be one important part of the closure of a landfill because it reduces leachate waters by evaporation and helps a landfill merge into the surroundings and returns the land into usage. The landscaping of a landfill depends on its size, location and enduse. A landfill near a large city which is planned for recreational use needs totally different landscaping from a small landfill in a remote district. However, the aim of landscaping for all types of landfills should be that they cannot be recognized as former landfills and even improve the original site.

## 2.11 Removal of landfills

Some landfills have been transferred to other places in Finland for different reasons. The Kuusilahti landfill containing oil wastes in Hämeenlinna was moved to the Karanoja landfill in Hämeenlinna in 1988–1989. The amount of wastes was 8 000 m<sup>3</sup>, moving distance 20 km and costs were about 3.6 million FIM. (Virtanen, E. 1994, personal communication, city of Hämeenlinna).

The Noljaakka landfill in Joensuu was removed in 1987 by the city to another place. The amount of the waste was 58 000 m<sup>3</sup> and costs were 703 000 FIM. (Insinööritoimisto Paavo Ristola 1988). Half of the landfill (200 000 m<sup>3</sup>) in Lakalaiva, Tampere was removed to build a motorway in 1990 (Viatak Oy 1988). The proposed removal plans of the Luokkisuo landfill in Kuopio were due to the contamination of groundwater caused by the landfill, but the move has not been realized. Partial tightening of landfills with vertical structures has been done in several landfills in Finland.

## 2.12 Control of leachate waters

The control of leachate waters of landfill was very uneven due to the great differences in size, location and type of landfills. The control could vary from a one-off sample to several annually taken samples. About 40 % of landfills were or have been under control. About one half of these landfills (31) was in the estimation of environmental consequences (Chapter 2.13). The majority of landfills excluded were so old that there were no control results or they were no longer a risk to the environment (Fig. 11).

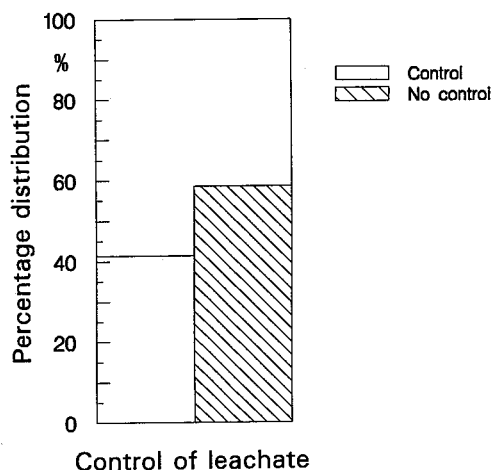


Fig. 11. The control of leachate waters of landfills as a percentage distribution.

### 2.13 Environmental consequences of landfills

Two landfills have contaminated groundwaters. Seven landfills have caused changes in the groundwaters but they were not yet serious enough to be classified as contaminating landfills. The situation, however, needed control. Sixteen landfills have caused changes to the ground- and surface waters but the changes were not significant, due to the location of the landfills or other greater contamination sources in the area. One landfill has caused for many years, since closure, a higher contamination in surface waters around the landfill. A lower level of contamination was discovered after closure around three landfills. Fig. 12 shows results as percentage distributions. The following sources were used in the estimation of environmental consequences of landfills: Assmuth *et al.* (1990), Espoon kaupungin tekninen virasto (1990), Heinolan mlk (1988), Helsingin kaupungin vesi- ja viemärlaitos (1989), Helsingin kaupungin ympäristönsuojelulautakunta (1988), Insinööritoimisto Paavo Ristola Oy (1988, 1990), Jyväskylän yliopisto, ympäristöntutkimuskeskus (1988), Kokemäenjoen vesistön vesiensuojeluyhdistys (1990), Lounais-Suomen vesiensuojeluyhdistys (1990), Maa ja Vesi Oy (1988), Maa ja Vesi Oy (1990 a, b, c), Peura *et al.* (1988), Savo-Karjalan vesiensuojeluyhdistys (1989, 1990 a, b), Suolahden kaupunki (1990), Suunnittelukeskus Oy (1990).

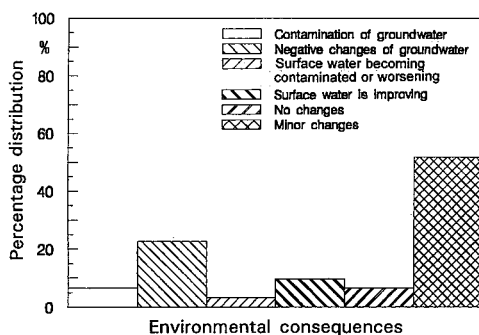


Fig. 12. Environmental consequences of landfills as a percentage distribution.

### 3 Conclusions

In the survey it was clearly seen that landfills in Finland did not fulfill the requirements of modern landfill technology and the environmental requirements concerning planning, construction, minimization of leachate waters, landscaping and enduse. The observed deficiencies were due to the fact that the research of waste management is a new science and planners of waste management have not had research results available for the planning of surface structures. Many failures of sludge ponds at landfills, before dam safety legislation, were also, in general, because structures have not been planned and built properly.

On the basis of this survey a research project was developed for further research:

- to make recommendations for measures to improve practice of landfill coverage in Finnish conditions
- to make literature research concerning surface structures and factors affecting them e.g. waste characteristics, compression, settlement and compaction of waste, landfill gas, vegetation and landscaping
- to make choice of surface structure types for Finnish conditions
- to develop and test the landfill cover model for closure of landfills for Finnish conditions
- to combine the results of the study with the aspects to be considered in the closing of landfills.

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**Appendix 3**

**The variables of LCAM**

**Contents**

<b>1 General .....</b>	<b>136</b>
<b>2 The characteristics of the soil layers .....</b>	<b>136</b>
<b>3 The limiting values related to drainage and infiltration .....</b>	<b>137</b>
<b>4 Parameters related to the plant stand .....</b>	<b>138</b>
<b>5 The variables determined in the program .....</b>	<b>139</b>

## Appendix 3

### The variables of LCAM

#### 1 General

The variables required in LCAM are classified into three categories:

- the physical characteristics of the soil layers
- the required parameters in calculating the infiltration, surface runoff and surface layer runoff which have only a partial physical interpretation
- empirical variables which affect the quality and condition of the plant stand.

After the selection of the weather conditions, the user is requested to choose one of the following alternatives:

- 1 = Adjust or correct the characteristics of the soil types
- 2 = Adjust the variables related to infiltration and drainage
- 3 = Adjust the variables related to the plant stand
- 4 = Calculate with the values of the current variables
- 5 = Output of the calculation in graphic form
- 9 = Terminate the performance of the program.

If the user wants to adjust or correct the variables used in the calculations, then by selecting alternative 1, 2 or 3, the values of the parameters of the different categories can be changed. Each parameter has been given in advance with the smallest and largest possible value which the user cannot go over or below. The program automatically makes sure that the value of the variable stays within permissible limits.

In the following chapters all the required parameters of the LCAM are demonstrated, their minimum and maximum values are given, and an estimation is given whether it is necessary to change the value of the parameter or not.

It is worth noting that the presented minimum and maximum values, e.g. as far as hydraulic conductivity and layer thickness are concerned, do not refer to the minimum values used in planning but instead refer to the minimum and maximum values accepted by LCAM.

#### 2 The characteristics of the soil layers

##### *A usable porosity for the plants of the surface layer*

This variable describes the difference of the moisture content between the moisture saturation and the so-called wilting point by volume (not as percentages). The most likely variation range for the parameters in question is 0.3–0.5. The value of the parameter is worth selecting individually.

Minimum value = 0.15. Maximum value = 0.7.

Values used in the testing of LCAM: Seutula 0.4, Hämeenlinna 0.37, Kuopio 0.40, Eura 0.35. Values used in the simulations with LCAM: 0.4.

##### *The thickness of the surface layer (mm)*

When the thickness of the surface layer (mm) is multiplied by the usable porosity for the plants, the maximum amount of water available for evaporation is obtained,  $W_{\max}$ .

Minimum = 10. Maximum = 1000.

Values used in the testing of LCAM: Seutula 300, Hämeenlinna 750, Kuopio 750, Eura 350. Values used in the simulations with LCAM: 500.

##### *The initial value of the soil water storage in the spring*

The initial value in calculating the soil water storage of the surface layer is given as a relative share of the maximum value. A suitable value is probably between 0.5–0.8.

Minimum value = 0.3. Maximum value = 1.0.

Values used in the testing of LCAM: Seutula 0.8, Hämeenlinna 0.8, Kuopio 0.75, Eura 0.80. Values used in the simulations with LCAM: 0.7.

##### *The hydraulic conductivity of the surface layer ( $m\ s^{-1}$ )*

The hydraulic conductivity of the surface layer affects mainly the so-called quantity of the surface layer drainage. In other words, the drainage component which moves above the hydraulic barrier in the surface layer. It is worth selecting the value individually.

Minimum value =  $10^{-8}$ . Maximum value =  $10^{-3}$ .

Values used in the testing of LCAM: Seutula  $10^{-6.3}$ ,  $10^{-7.0}$ ,  $10^{-7.8}$ , Hämeenlinna  $10^{-6.5}$ ,  $10^{-7.0}$ ,  $10^{-8.0}$ , Kuopio  $10^{-6.5}$ ,  $10^{-7.5}$ ,  $10^{-8.1}$ , Eura  $10^{-6.2}$ ,  $10^{-7.0}$ ,  $10^{-7.8}$ . Values used in the simulations with LCAM:  $10^{-5}$ .

*The limiting value of the soil water storage (relative saturation degree), below which real evaporation is smaller than potential*

If the soil is too dry the plant stand is unable to evaporate with maximum efficiency, instead part of the stomata are closed and real evaporation remains smaller than the potential. On the basis of findings from literature, the dryness of the soil begins to restrict evaporation when the pF-value is greater than 2.5–3.0, which corresponds in many soil types to the relative saturation degree of 0.5–0.8.

Minimum value = 0.5. Maximum value = 0.9.

Values used in the testing of LCAM: Seutula 0.80, Hämeenlinna 0.75, Kuopio 0.75, Eura 0.80. Values used in the simulations with LCAM: 0.7.

*The thickness of the hydraulic barrier (mm)*

The quantity of water going through the hydraulic barrier depends on the hydraulic conductivity and the thickness of the hydraulic barrier and the difference of the hydraulic potential between the upper and lower surfaces of the hydraulic barrier. Hydraulic potential on the lower surface of the hydraulic barrier is given as start data and the model calculates the hydraulic potential on the upper surface of the hydraulic barrier.

Minimum value = 100. Maximum value = 1000. Values used in the simulations with LCAM: 600.

*The hydraulic conductivity of the hydraulic barrier ( $m\ s^{-1}$ )*

The hydraulic conductivity of the hydraulic barrier has a linear connection with the infiltrating quantities of water: the smaller the hydraulic conductivity, the less water infiltrates to the waste. Minimum value =  $10^{-11}$ . Maximum value =  $10^{-5}$ . Values used in the simulations with the LCAM:  $10^{-5}$ – $10^{-9}$ .

*The drainage layer: thickness (mm), hydraulic conductivity ( $m\ s^{-1}$ )*

The thickness of the drainage layer can vary between 0–500 mm, the slope between 0–20 % and the hydraulic conductivity between  $10^{-3}$ – $10^{-5}\ m\ s^{-1}$ .

Values used in the simulations with LCAM: thickness 200, 400 and hydraulic conductivity  $10^{-4}$ .

### 3 The limiting values related to drainage and infiltration

*The tilt of the slope (gradient)*

In calculating the surface layer drainage, the tilt of the slope is needed as a percentage.

Minimum value = 0 %. Maximum value = 20 %.

Values used in the testing of LCAM: Seutula 5, Hämeenlinna 7, Kuopio 6, Eura 8. Values used in the simulations with LCAM: 5.

*The average length of the slope (m)*

The average length of the slope causes the relative effect of the surface layer drainage to decrease when the slope length increases.

Minimum value = 1. Maximum value = 400.

Values used in the testing of LCAM: Seutula 100, Hämeenlinna 80, Kuopio 70, Eura 30. Values used in the simulations with LCAM: 80.

*The start of the limiting value of the surface layer runoff*

In the model it is assumed that the relative saturation degree of the surface layer ( $W/W_{\max}$ ) must be greater than its limiting value before surface layer drainage can occur. It is difficult to determine an exact value for the variable but it is likely to be between 0.4–0.8.

Minimum value = 0.10. Maximum value = 0.90.

Values used in the testing of LCAM: Seutula 0.6, Hämeenlinna 0.65, Kuopio 0.6, Eura 0.65. Values used in the simulations with LCAM: 0.50.

*The distance of drainage ditches in the direction of the slope (m)*

In light of the greatest tilt, drainage ditches placed in cross direction remove water from the vegetation layer where the quantity of water susceptible

to infiltration decreases. If the user selects a distance between the ditches greater than 50 metres, then the program assumes that the drainage ditches have not been built at all.

Minimum value = 3. Maximum value = 100.

No drainage ditches in the testings and simulations

*The relative saturation degree of the surface layer in which infiltration begins to occur*

This limiting value depicts the so-called field capacity (pF-value 2) corresponding to the relative saturation degree, which many soils used as surface layers have, and is between 0.60–0.90.

Minimum value = 0.50. Maximum value = 0.95.

Values used in the testing of LCAM: Seutula 0.73, Hämeenlinna 0.65, Kuopio 0.75, Eura 0.75. Values used in the simulations with LCAM: 0.70.

*The quantity depicting the unevenness of the surface (mm)*

If the surface layer is completely saturated with water, then additional rain may cause so-called surface runoff. If the surface of the soil is uneven, then extra rain first forms as ponds in the lower parts of the surface. The variable given here depicts the unevenness of the surface, and thus the greater the variable is, the less surface drainage occurs. The value of the variable depicts the thickness of the water layer collected in the lower parts of the surface as though this layer would have been evenly distributed throughout the entire area of the landfill.

Minimum value = 0. Maximum value = 30.

Values used in the testing of LCAM: Seutula 20, Hämeenlinna 25, Kuopio 20, Eura 25. Values used in the simulations with LCAM: 15.

#### 4 Parameters related to the plant stand

*Type of plant stand*

0 = no growth at all

1 = grass

2 = treelike growth (e.g. willow thicket)

Minimum value = 0. Maximum value = 2.

*The condition of the plant stand*

The condition of the plant stand primarily affects the development of the leaf surface of plants. The more plants are assumed to suffer from dryness or other stress (e.g. poor soil, poor nutrients), the worse the condition of the plant stand and the smaller the proportion of evaporation.

Minimum value = 0. Maximum value = 10.

Values used in the testing of LCAM: 0. Values used in the simulations with LCAM: 0–10.

*The damping of radiation in the plant stand*

The radiation absorbed by the plant stand is calculated in LCAM using the leaf surface and the radiation damping factor. In literature the latter variable has recommended values between 0.5 and 0.8. Constantly using the value 0.6 is completely justified.

Minimum value = 0.4. Maximum value = 0.8.

Values used in the simulations of LCAM: 0.60.

*The relative evaporation from the bare ground*

Evaporation from the bare ground is clearly smaller than the amount of water evaporated by the plant stand. The ratio of the evaporation of the bare ground to the evaporation of the ground completely covered by plant growth has to be given to LCAM. For example, according to Ettala's measurements, the evaporation of bare ground is approx. 50–60 % of that of a watered willow thicket.

Minimum value = 0.25. Maximum value = 0.7.

Values used in the testing and in the simulations of LCAM: 0.50.

*Relative evaporation / grass*

In a corresponding way to the aforementioned, the ratio is determined by dividing the maximum evaporation of grass by the evaporation of ground completely covered by plant growth. The value of the ratio is close to 1.

Minimum value = 0.7. Maximum value = 1.00.

Values used in the simulations with LCAM: 0.80.

*The relative evaporation / tree growth*

In a corresponding way to the aforementioned, the ratio is determined by dividing the maximum evap-

oration of tree growth by ground completely covered by plant growth. The ratio for willow thicket is 1.0, with some exceptions. However, the ratio value for a sparse birch grove must be smaller. Minimum value = 0.5. Maximum value = 1.0. Values used in the simulations of LCAM: 0.90.

#### *Maximum interception storage / grass*

Some of the rain is retained on the surfaces of plants and is immediately susceptible to evaporation once the rain has ceased. This quantity of interception evaporation depends on the density of the plant growth and leaf surface. LCAM calculates the entire time the plants' leaf surface LAI, and the size of the maximum interception (mm) is obtained by multiplying the maximum size of the interception storage LAI by the entered parameter. In literature the value of the variable for grass is approx. 0.1–0.2.

Minimum value = 0.05. Maximum value 0.25. Values used in the simulations of LCAM: 0.10.

#### *Maximum interception storage / willow thicket (dense tree growth)*

This is the corresponding value as before, but for dense tree growth. According to Ettala (1987a,

1988a), the proportion of interception may be nearly a third of the total rain. The most likely value of the parameter is approx. 0.25–0.50. Minimum value = 0.1. Maximum value = 0.6. Values used in the simulations of LCAM: 0.10.

## **5 The variables determined in the program**

The development of the plant stand's leaf surface is determined directly in the program. In the model it is assumed that the growth period begins when an effective temperature (when the average temperature exceeds +5 °C) becomes greater than some limiting value. After this the program begins to grow the leaf surface (LAI) which reaches its maximum of 5.0 when some other effective temperature limiting value has been reached. The plant stand remains green until the third critical temperature has been reached in autumn, after which the LAI begins to decrease. The limiting values of the temperatures have been obtained from the Agricultural Department of the University of Helsinki.



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### Book chapters:

Tamminen P. & Starr M. 1990. A survey of forest soil properties related to soil acidification in Southern Finland. In: Kauppi P., Anttila P. & Kenttämies K. (eds.), *Acidification in Finland*, Springer, Berlin, pp. 237-251.

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